SECTION 2 - HYDROGEOLOGIC INFORMATION

2.1 Elevation of Land Surface at Well Location.

The surface elevation at the proposed carbon sequestration site is approximately 675 feet above mean sea level (MSL), as referenced from the Forsyth, Illinois, United States Geological Survey (USGS) 7.5-minute topographic quadrangle map.

2.2 Faults, Known or Suspected Within the Area of Review.

The IL-ICCS site is located in an area with no evidence of geological folds and faults. Regional mapping (Nelson, 1995) has indicated that there are no regional faults or fractures mapped within a 15-mile radius of the proposed site (Figure 2-1). Seismic reflection data were acquired near the site in order to characterize the geologic structure of the study area. Specifically, seismic surveys were undertaken to determine the presence or absence of faults and folds in the vicinity of the proposed well site. A 2D seismic survey in the vicinity of the proposed site, acquired prior to the initiation of the IBDP well, indicated that the overall structure of the area consists of nearly flat strata dipping slightly (< 1°) towards the southeast. These surveys also indicated that the morphology of the top of the Precambrian surface is not flat, and there are small undulations in the bedding of the strata (Figures 2-2 through 2-4). Study of 3D seismic reflection data acquired for the Illinois Basin Decatur Project (IBDP) site indicates that there are no resolvable faults through either the Mt. Simon Sandstone or the Eau Claire Formation (Figure 2-4). In addition, this data indicate that there is no folding in site area.

In January 2011, additional 3D seismic data were acquired in the area of the proposed ICCS injection site. Processing of this 3D seismic dataset was completed in August 2011. The resulting interpretations (Appendix M) support the earlier interpretations on the geological structure of the area. The 2011 data provide even better resolution than previous seismic data in the area due to improved Vibroseis sweep parameters, optimal frozen conditions during the time of acquisition, and other improvements. These data indicate that resolvable (from seismic reflection data) faults and folds are not present. The irregularities in the geomorphology of the Precambrian surface are displayed in increased detail, indicating the occurrence of subtle upland hills and intervening lowlands.

2.2.1 Seismic History and Risk

Since 1973, two earthquakes have been recorded within 100 km of the proposed injection site: a magnitude 3.0 quake on April 24, 1990 in Coles County approximately 41 miles to the southeast, and a magnitude 3.2 quake on January 29, 1993 in Fayette County approximately 58 miles to the south-southwest (http://earthquake.usgs.gov/earthquakes/eqarchives/epic/epic_circ.php, USGS Earthquake Search, as of March 17, 2011).

The relative seismic risk of the Decatur location is considered minimal. The probability of an earthquake of magnitude 5.0 or greater within 50 years and within 50 km is less than 1% (USGS 2009 PSHA model for Decatur, Illinois, https://geohazards.usgs.gov/eqprob/2009/). There exists a 2% probability that the Peak Ground Acceleration due to seismic activity will exceed 10% G within 50 years (http://earthquake.usgs.gov/earthquakes/states/illinois/hazards.php). Thus, the risk of seismic activity breaching the integrity of the well or the injection formation is considered minimal.

Source:

Leetaru, H., 2011. Personal communication, Illinois State Geological Survey

Nelson, W.J., 1995. Structural features in Illinois, Illinois State Geological Survey Bulletin 100, 144 p.

2.3 Maps and Cross Sections.

Two vertical cross-sections and the location map of the proposed injection site are shown in Figures 2-5 through 2-7. Based on interpretation of 3D seismic data collected for the IBDP, two cross-sections were developed showing the bedrock stratigraphy at the proposed well site. Line A-A' is a west to east cross-section, while Line B-B' is a south to north cross-section. The surface elevations along the seismic lines range from approximately 660 feet to 680 feet. The cross-sections provide elevations on the y axis and have no vertical exaggeration. The seismic data were analyzed and interpreted by Alan Brown (Schlumberger Carbon Services) and Hannes Leetaru (ISGS). The cross-sections were prepared by Valerie Smith, Schlumberger Carbon Services.

Excluding the IBDP injection well (herein referenced as CCS #1) and the IBDP verification well (herein referenced as Verification Well #1), no other deep wells penetrate the Eminence, Ironton-Galesville, Eau Clare or Mt. Simon Formations (Figure 2-8) within the area of review (reference Section 5 for area of review information). All of the deeper horizons are projected from regional mapping. Therefore, well locations are not displayed on the cross-sections (Figures 2-6 and 2-7).

2.4 Injection Zone.

Information on the injection zone (Mt. Simon Sandstone) is based on regional geologic information from previous ISGS studies and reports, and on specific data obtained from the CCS #1 well installation (Frommelt, 2010).

Regional

The thickest and most widespread saline water bearing reservoir (saline reservoir) in the Illinois Basin is the Cambrian-age Mt. Simon Sandstone (Figure 2-8). It is overlain by the Cambrian Eau Claire Formation, a regionally extensive very low-permeability unit, and underlain by Precambrian granitic basement. There are records of 21 wells in central and southern Illinois that were drilled into the Mt. Simon (to depths greater than 4,500 feet). Many of the 21 wells penetrate less than a few hundred feet into the Mt. Simon. In addition, most wells are older and lack a suite of modern geophysical logs suitable for petrophysical analysis. Although comprehensive reservoir data for the Mt. Simon are lacking, there are sufficient data to demonstrate its regional presence. In the northern half of Illinois, the Mt. Simon is used for natural gas storage in several locations. Detailed reservoir data are available from these projects. Excluding CCS #1 and Verification Well #1, the closest Mt. Simon penetration to the ADM site is about 17 miles southeast in Moultrie County, the Sanders Harrison #1 (Harrison #1). Only the top two hundred feet of the Mt. Simon was drilled. Based on logs from the IBDP injection and verification wells, the Mt. Simon thickness at the proposed injection site is anticipated to be about 1,500 feet.

Sample descriptions from the Harrison #1 well indicate that there is good porosity in the top 200 feet of the Mt. Simon. The nearest well with a porosity log for the entire thickness of the Mt. Simon, the Humble Oil Weaber-Horn #1 well (Weaber-Horn #1), was drilled on the Loudon Field anticline in Fayette County, a major oilfield 51 miles south of the ADM site. The Weaber-Horn #1 drilled through 1,300 feet of Mt. Simon before drilling into the Precambrian granite. The top of the Mt. Simon at the Weaber-Horn #1 well was at 7,000 feet and, based on calculations from wireline logs, the sandstone formation's gross thickness had an average porosity of about 12 percent. The Weaber-Horn #1 well log porosity data are similar to those found in deeper wells at the Manlove gas storage field (Manlove Field) in Champaign County, approximately 37 miles northeast of the ADM site. The Manlove Field is the deepest Mt. Simon gas storage field in the Illinois Basin and, prior to CCS#1, provided one of the most complete legacy reservoir data sets for characterization of the deep Mt. Simon. The permeability at the Weaber-Horn #1 well and the ADM site are expected to be similar to those at Manlove Field. A north-south trending cross section A-A' across the Hinton #7 , Harrison #1, CCS #1, and Weaber-Horn #1 wells (Figure 2-9) shows that the Mt. Simon should be porous and thick at the proposed site.

Regional Geology: Depositional Environment

The deposition of the Mt. Simon Sandstone has commonly been interpreted to be a shallow, subtidal marine environment. Most of these studies, however, were based on either surface study of the upper part of the Mt. Simon or on study of outcrops in Wisconsin or the Ozark Dome. Based on studies of the samples and logs of the CCS #1 well, the upper part of the Mt. Simon is interpreted to have been deposited in a tidally influenced system similar to the reservoirs used for natural gas storage in northern Illinois. However, the basal 600 feet of Mt. Simon sandstone is an arkosic sandstone that was originally deposited in a braided river – alluvial fan system. This lower Mt. Simon Sandstone is the principal target reservoir for sequestration because of the high secondary porosity and permeability formed by the dissolution of feldspar grains.

Source:

Driese, S.G., C.W. Byers, and R.H. Dott, Jr., 1981. Tidal deposition in the basal Upper Cambrian Mt. Simon Formation in Wisconsin: Journal of Sedimentary Petrology, v. 51, no. 2, p. 367–381.

Droste, J.B., and R.H. Shaver, 1983. Atlas of early and middle Paleozoic paleogeography of the southern Great Lakes area: Indiana Department of Natural Resources, Indiana Geological Survey, Special Report 32, 32 p.

Frommelt, D., 2010. Letter to the Illinois Environmental Protection Agency, Subject: CCS Well #1 Completion Report, Archer Daniels Midland Company – UIC Permit UIC-012-ADM, dated May 5, 2010 [Appendix L].

Kolata, D.R., 1991. Illinois basin geometry, in M.W. Leighton, D.R. Kolata, D.F. Oltz, and J.J. Eidel, eds., Interior cratonic basins: American Association of Petroleum Geologists, Memoir 51, p. 197.

Sargent, M.L., and Z. Lasemi, 1993. Tidally dominated depositional environment for the Mt. Simon Sandstone in central Illinois: Great Lakes Section, Geological Society of America, Abstracts and Programs, v. 25, no. 3, p. 78.

2.4.1 Geologic Name(s) of Injection Zone.

The proposed injection zone (refer to Section 2.4.2 for anticipated depth) is the Cambrian-age Mt. Simon Sandstone. CO_2 injected through the well will be contained in the injection zone and will flow into the Mt. Simon at the injection interval. The injection interval is a portion of the Mt. Simon where the injection well is perforated.

2.4.2 Depth Interval of Injection Zone Beneath Land Surface.

The Mt. Simon was found at a depth of 5,545 feet to 7,051 feet (Frommelt, 2010) based on borehole logging data for the CCS #1 well. An interval of high porosity and permeability was identified at the base of the Mt. Simon. This basal interval was selected as the initial injection interval for the CCS #1 well and was perforated from 6,982 to 7,050 feet.

For the IL-ICCS CO_2 injection project, the planned injection interval is a relatively high permeability zone in the lower Mt. Simon. The approximate gross interval is 6,700 to 7,050 feet. The perforation depths are to be finalized after drilling and will be reported in the well completion report.

2.4.3. Characteristics of the Injection Zone.

Based on the data from the CCS #1 well (Frommelt, 2010), the proposed injection zone is expected to be a porous and permeable sandstone that, in some intervals, is an arkosic sandstone. Grain size varies from very-fine grained to coarse grained. The sandstones are primarily composed of quartz, but some intervals contain more than 15 percent feldspar. Diagenetic clay minerals are not common.

2.4.3.1 Lithologic Description

The Mt. Simon Sandstone regionally varies in lithology from conglomerates to sandstone to shale. Six dominant lithofacies have been recognized: cobble conglomerate, stratified gravel conglomerate, poorly-sorted sandstone, well-sorted sandstone, interstratified sandstone and shale, and shale (Bowen et al., 2011).

The poorly-sorted sandstone lithofacies is the most common regionally and within the Mt. Simon in the CCS #1 well, which contains discrete intervals of predominantly finer-grained sandstone and coarser-grained sandstone. The basal portions of some of the coarser-grained strata are often conglomeratic. In addition, the arkosic interval at the base of the Mt. Simon in the CCS #1 well is about 40 feet thick and interbeds of dark gray shale laminae occur between some of the sandstone strata (Morse and Leetaru, 2005).

The principal cementing material is quartz in the form of overgrowths and feldspar precipitation. Most of the very fine-grained intervals contain large amounts of detrital and authigenic potassium feldspar. The lower part of the Mt. Simon tends to have more feldspar-rich zones than the upper part. These zones consequently tend to have greater feldspar framework grain dissolution and increased porosity. These feldspar-rich intervals may have the best reservoir characteristics for sequestration (Bowen et al. 2011).

Source:
Bowen, B.B., R.I. Ochoa, N.D. Wilkens, J. Brophy, T.R. Lovell, N. Fischietto, C.R Medina, and J.A. Rupp, 2011. Depositional and Diagenetic Variability Within the Cambrian Mount Simon Sandstone: Implications for Carbon Dioxide Sequestration: Environmental Geosciences, v. 18, p. 69-89.

Morse, D.G., and H.E. Leetaru, 2005. Reservoir characterization and three-dimensional models of Mt. Simon Gas Storage Fields in the Illinois Basin: Illinois State Geological Survey, Circular 567, 72 p. CD-ROM.

2.4.3.2 Injection Zone Thickness

The entire (gross) Mt. Simon interval is estimated to be 1,500 feet in thickness, based on CCS #1 well logs. Drilling and testing of the CCS #1 injection well has determined the thickness of individual porous intervals.

While CO_2 may be stored in the entire thickness, the perforated or injection interval will be much smaller and is planned for a high porosity zone relatively deep in the Mt. Simon. Injectivity is primarily a product of net formation thickness (b) and permeability (k) or permeability-thickness (kb), while storage volume is primarily a function of net formation thickness and effective porosity. Because of the thickness and permeability of the Mt. Simon noted in the CCS #1 well, Weaber-Horn, and Hinton wells, nominal injection capacity of 3,000 metric tonnes per day (MT/day) is anticipated to be highly probable. CO_2 reservoir flow modeling (see Section 5.4 of this application) shows that the lower zone can readily accept the 3,000 MT/day injection rate.

2.4.3.3 Fracture Pressure at Top of Injection Zone

At the CCS #1 well, a step-rate test (Earlougher, 1977) was conducted on September 26, 2009 into the initial 25-foot perforated interval from 7,025 to 7,050 feet at the base of the Mt. Simon. [Another set of perforations was added (6,982 to 7,012') at a later date. More details are available in (UIC Form 4h, CCS Well #1 Completion Report, April 29, 2010), included as Appendix L.] The primary purpose of the test was to estimate the fracture pressure of the injection interval. A bottom-hole pressure gauge with surface readout was used. The pressure gauge was located at 6,891 feet inside the tubing, 134 feet above the uppermost perforation. All tests were done by injecting water. CO_2 or other compressibile fluids were not used. Water with clay-stabilizing potassium chloride was injected in 1.0 barrel per minute (bpm) increments starting at 2.0 bpm (84 gallons per min, gpm) to 8.0 bpm (336 gpm). Each rate was maintained for approximately 45 minutes. The pressure near the end of each injection period was plotted against the injection rate to determine the fracture pressure (Figure 2-10).

In Figure 2-10, the first line with the greater slope at lower rates and pressure is the perforated interval's response to water injection prior to fracturing. The second line with the lower slope at higher rates and pressures is after the fracture developed. The intersection of the two straight lines is 4,966 psig. To find the fracture pressure at the top of the perforations, the hydrostatic pressure of the water (0.433 psi/ft) in the wellbore between 6,891 (location of pressure gauge) and 7,025 feet was added to the 4,966 psig. The fracture pressure at 7,025 feet is 5,024 psig. This corresponds to a fracture gradient of 0.715 psi/ft.

Based on this fracture gradient, the fracture pressure at the estimated depth of the uppermost perforation requested in the permit for this well (6,700 ft) is calculated to be 4,790 psi.

Source:
Earlougher, Jr., R.C., 1977. *Advances in Well Test Analysis*, Monograph Series, Society of Petroleum Engineers of AIME, Dallas.

2.4.3.4 Effective Porosity

Compensated neutron and litho-density open-hole porosity logs were run in the CCS #1 well. The neutron and density logs provide total porosity data (all pore space). Effective porosity, as shown in this section, is considered to be connected pore space only which includes the effect of irreducible brine saturation (Note: irreducible water saturation is the lowest water saturation, S_{wi}, that can be achieved in a core plug by displacing the water by oil or gas). Effective porosity was determined by lab testing using helium porosimetery on a limited number of core plug samples. See Appendix L of the CCS #1 well completion report (Frommelt, 2010) for additional discussion about the helium porosimetery method.

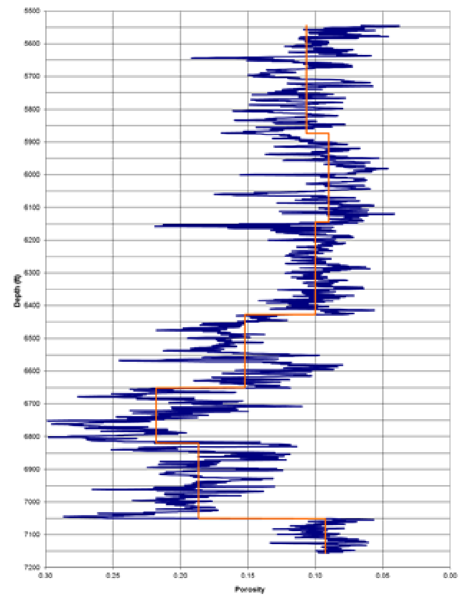
Comparison of the neutron-density crossplot porosity (average neutron and density porosity) and core porosity (Figure 2-11) showed similar values. Additionally, the open-hole log based porosity was classified using Schlumberger ELemantal Log Analysis (ELAN) as described in CCS#1 Geophysical Log Descriptive Report found in Appendix K.

Based on porosity trends, there are 7 major sub-intervals present in the Mt. Simon. Table 2-1 lists the intervals identified and the average effective porosity of each. Based on the neutron-density crossplot porosity, the 68-foot injection interval for CCS #1 (6,982-7,050 feet) had an average effective porosity of 21.0%.

Reservoir modeling for CCS#2 injection, as discussed in Section 5, accounts for irreducible water and assumes a S_{wi} of 35%. This value of S_{wi} may ultimately be adjusted in the model to help the model match actual injection results.

Table 2-1: Average effective porosity based on the neutron-density crossplot porosity for CCS #1. The seven sub-intervals were selected based on major changes in the trend of porosity from the neutron-density logs. The log based porosity trends were also cross checked with other log data (e.g. resistivity) and available core data. A figure showing the seven zones is shown to the right of the table.

Sub-Interval (feet)	Effective Porosity (%)
5,545-5,874	10.8
5,874-6,144	8.72
6,144-6,428	10.1
6,428-6,650	15.2
6,650-6,820	21.8
6,820-7,050	18.7
7,050-7,155	9.84



2.4.3.5 Intrinsic Permeability

Intrinsic permeability, *k*, was directly available from the results of the core analyses and well testing of CCS #1. However, to estimate permeability over a larger interval where core is not available, a relationship between core permeability and log porosity is required.

Core Analysis

A core porosity-permeability transform was developed (Figure 2-12) based on a visual grain size description. This transform was used with the crossplotted neutron-density porosity and cementation exponent (m) calculated using Archie's equation (Archie, 1942) to estimate permeability with depth. (See following paragraph for more information on the values used in the Archie equation.) Average permeability for sub-intervals of the Mt. Simon for CCS #1 is in Table 2-2. Based on the neutron-density crossplot porosity and the core porosity-permeability transform, the 68-foot injection (perforated) interval (6,982-7,050 feet) in CCS #1 has a geometrical average intrinsic permeability of 194 mD (Frommelt, 2010).

In Archie's equation in the format of Sw^n=(a/(phi^m))*Rw/Rt, it was assumed that Sw^n = 1. (Rt = fluid saturated rock resistivity, phi = porosity, Rw = brine resisitivity, m = cementation exponent, a = tortuosity factor, Sw = brine saturation, n = saturation exponent) Deep resisitivity measurements from open hole logs on CCS#1 were used for Rt. Crossplotted neutron-density porosity was used for phi and an "a" of 1 was used. Rw was calculated from temperature corrected conductivity measurements made from fluid samples. After solving for "m", considerable effort was made adjusting the classifications of "m" (Figure 2-12) to produce the best match between estimated permeability and core-measured values of permeablitilty.

It is apparent in Figure 2-12 that permeability and porosity in the Mt. Simon formation are not directly related. A coarse grain sandstone section can have similar porosity to a finer grain sandstone section, yet the permeabilities can be higher in the coarse grain section. Grain size is not the only factor in controlling permeability. Diagenesis is believed to play a significant role.

[Other work relating porosity and permeability was also done using extensive use of wireline logs, including nuclear magnetic resonance methods and is discussed briefly in the Modeling section (Section 5) and Appendix K of this application.]

Table 2-2: Average intrinsic permeability based on a transform of core permeability and core porosity related to the neutron-density crossplot porosity for the sub-intervals shown. The seven sub-intervals were selected based on major changes in the trend of porosity from the neutron-density logs.

Sub-Interval (feet)	Intrinsic Permeability (mD)
5,545-5,900	19.4
5,900-6,150	10.2
6,150-6,430	8.44
6,430-6,650	8.21
6,650-6,820	8.64
6,820-7,050	107
7,050-7,165	4.37

Source:
Archie, G.E., 1942. The electrical resistivity log as an aid in determining some reservoir characteristics: Journal of Petroleum Technology, v. 5, p. 54-62.

Well Testing
Step rate / pressure falloff (PFO) tests of varying duration were conducted in September and October 2009 as part of the initial completion of CCS #1 (Frommelt, 2010). A pressure falloff test involves two segments. During the first test segment, the reservoir is stressed by injecting fluid, which increases the reservoir pressure. During the second test segment, the reservoir pressure is monitored as it returns to its pre-test pressure. The initial perforations in the injection interval were 7,025 to 7,050 feet. Water treated with a clay-stabilizing potassium chloride was injected at 1.5 to 2.0 barrels per minute (bpm) (63 to 84 gallons per minute) for nearly two hours. A 19.5 hour PFO followed this injection period.

After this test, these perforations were acidized and a step-rate test was conducted. For the second step-rate / pressure fall off test, treated water was injected at 3.1 bpm (130 gpm) for five hours, while pressure was monitored for approximately 45 hours.

The third PFO test was conducted after the well was perforated and stimulated. An additional 30 feet of perforations were added at 6,982 to 7,012 feet. The perforated zone received a second acid treatment. Additional information regarding perforations and acid treatment are described in the CCS #1 Completion Report, Appendix L (Frommelt, 2010). For the third PFO test, the treated water was injected at an increasing rate of 3.1 to 4.2 bpm (130 to 176 gpm) over 6.5 hours and then at 4.2 bpm (176 gpm) for an additional 6.5 hours. During this third PFO test, pressure was monitored for 105 hours.

Pressure Transient Analyses
PIE pressure transient software was used to analyze the pressure data for reservoir flow properties. Conventional semi-log, log-log and nonlinear regression analyses were used to analyze the data. (Well-Test Solutions, Ltd., http://welltestsolutions.com/index.html)

During the first PFO, because only 25 feet of perforations were open in a very large vertical formation (gross thickness 1,506 feet), a partial penetration or partial completion effect was expected. The derivative (log-log plot) of the falloff test is used to qualitatively identify reservoir features including the partial penetration effect (reference Figure 2-13) and to determine permeability. Two radial, 2-dimensional responses (horizontal derivative) were measured during this test between 0.1 and 1 hrs (PPNSTB) and 20 to 100 hrs (STABIL). The first period corresponds to radial flow across the 25 feet perforated interval; the second period corresponds to the pressure response across a larger thickness that would be between two much lower permeability sub-units. The transition between the two radial responses (SPHERE) is a spherical flow (3-dimensional flow) period that is influenced by vertical permeability or the ratio of vertical to horizontal permeability (k_v/k_h).

To observe the effect of the acid treatment and the second set of perforations to the overall injection interval, the derivatives of the three pressure falloff tests were overlain (Figure 2-14). The data between 0.1 and 1.0 hrs match relatively well and the data between 1.0 and 100 hrs match very well. Similar trends of the first radial period, transition and final radial period indicates that the second set of perforations did not change the permeability estimated from the pressure transient tests or contribute to the perforated interval. As such, the subsequent pressure transient analyses used a single layer, partial penetration model with 25 feet of perforations open at the base of the layer.

Simulation of the pressure transient data using analytical solutions (Figure 2-15), gave a permeability of 185 mD over 75 feet of vertical thickness. The transition period gave a vertical permeability over the 75 feet as 2.45 mD ($k_v/k_h = 0.0133$). The Mt. Simon initial pressure at CCS #1 at 7,025 feet is about 3,200 psig.

For the injection interval, the permeability estimates from the different methods are very close. Based on the neutron-density crossplot porosity and the core porosity-permeability transform, the 68-foot, injection (perforated) interval (6,982 to 7,050 feet) has an average intrinsic permeability of 194 mD. Using the PIE pressure transient software for the third PFO, permeability was estimated to be 185 mD over 75 feet of vertical thickness. Permeability for this same 75 feet of rock was calculated using core and well log analyses. The permeability from this analysis was estimated to be 182 mD.

Source:
Leetaru, H.E., D.G. Morse, R. Bauer, S. Frailey, D. Keefer, D. Kolata, C. Korose, E. Mehnert, S. Rittenhouse, J. Drahovzal, S. Fisher, J. McBride, 2005. Saline reservoirs as a sequestration target, in An Assessment of Geological Carbon Sequestration Options in the Illinois Basin, Final Report for U.S. DOE Contract: DE-FC26-03NT41994, Principal Investigator: Robert Finley, p 253-324

Frailey, S.M., Damico, J., Leetaru, H.E., 2010. Reservoir Characterization of the Mt. Simon Sandstone, Illinois Basin, USA, proceedings, 10th International Conference on Greenhouse Gas Control Technologies (GHGT-10), Amsterdam, September 19-23, 2010

2.4.3.6 Hydraulic Conductivity

Intrinsic permeability (k) and hydraulic conductivity (K) are related according to the following equation (Freeze and Cherry, 1979):

$$K = k \rho g / \mu$$

where ρ= fluid density
g= gravitational acceleration
μ= dynamic viscosity

Intrinsic permeability (k) is a property of the rock, while hydraulic conductivity (K) includes properties of the rock and fluid. Intrinsic permeability is also known as permeability and is discussed in Section 2.4.3.5. Formation water density and dynamic viscosity are discussed in Sections 2.4.4.3 and 2.4.4.4, respectively. For the range of viscosity and density discussed, the hydraulic conductivity will vary.

The 68-foot injection interval in CCS #1 (6,982 to 7,050 feet) had an average intrinsic permeability of 194 mD (see Section 2.4.3.5); this converts to a hydraulic conductivity of 3.9×10^{-4} cm/sec, using the water properties at this depth.

Source:
Freeze, R. A. and J. A. Cherry, 1979. *Groundwater*. Englewood Cliffs, N.J., Prentice-Hall, Inc.

2.4.3.7 Storage Coefficient

The storage coefficient or storativity, S, ranges from 5×10^{-5} to 5×10^{-3} for confined aquifers (Freeze and Cherry, 1979). S is commonly determined by well testing; however, S is a function of fluid compressibility (c_f) and rock compressibility (c_r) and can be estimated from the following equation:

$$S = \rho g h (c_r + \varphi c_f)$$

where φ= porosity
h= formation thickness
ρ= fluid density
g= gravitational acceleration

Rock compressibility can be expressed as the inverse of the bulk modulus (K_b) and in terms of the Young's modulus (E) and Poisson's ratio (v) (Huang and Rudnicki, 2006):

$$c_r = 1/K_b = 3(1 - 2v)/E$$

Fluid density is discussed in Section 2.4.4.3. Gravitational acceleration approximately equals 9.81 m/sec^2. For this calculation, the Mt. Simon is assumed to be 1,506 feet thick and have 13.2% porosity (φ). As discussed in Freeze and Cherry (1979), storage coefficient is a term used to describe the hydraulic properties of a confined aquifer. Thus, the entire aquifer thickness and an average effective porosity were used to estimate the storage coefficient. Young's modulus (E) and Poisson's ratio (v) were determined by Weatherford Laboratory (see CCS #1 Completion Report, Appendix L (Frommelt, 2010) for more details) for Mt. Simon samples collected at depths of 6,761 and 6,770 feet. These values were used to compute c_r using the equation shown above. These compressibility values are consistent with bulk compressibility values for sandstone reservoirs, which ranged from 6.5x10^{-5} to 2.7x10^{-4} MPa^{-1} at 7,000 psi (48.3 MPa) confining pressure (Zimmerman, 1991). Fluid compressibility (c_f) is known to vary with pressure and temperature changes (Huang and Rudnicki, 2006). Using two samples collected from CCS #1 (MDT-1 & MDT-4), fluid compressibility and storativity values were estimated (reference Section 2.4.4, Table 2-4).

Based on the range of values described here, storativity was estimated to range from 4.9x10^{-5} to 9.0x10^{-4} (Table 2-3). These values are consistent with values published by Freeze and Cherry (1979). "Storage coefficient" is a term used to describe the hydraulic properties of a confined aquifer and will not be influenced by residual water saturation. Storage coefficient is defined for groundwater flow, but not two-phase (e.g., water-air, water-CO_2) flow. As described in Freeze and Cherry (1979), the term has roots in aquifer testing and is best applied for describing 2D flow through aquifers. For two-phase flow problems where 3D flows may be important, porosity and permeability are better terms to use than storage coefficient and transmissivity.

Table 2-3. Estimates of rock (c_r) and fluid (c_f) compressibility and storativity (S) for CCS #1

Depth (ft)	Pressure (psi)	Pressure (MPa)	T (°C)	ρ (g/L)	c_r (1/Mpa)	c_f (1/Mpa)	Φ (-)	h (m)	S (vol/vol)
5772	2582.9	1.78E+01	48.8	1089.7	2.02E-04	2.04E-04	0.132	459.0	8.59E-04
7045	3206.1	2.21E+01	52.1	1123.5	2.02E-04	1.83E-04	0.132	459.0	9.00E-04
5772	2582.9	1.78E+01	48.8	1089.7	3.68E-05	2.04E-04	0.132	459.0	4.87E-05
7045	3206.1	2.21E+01	52.1	1123.5	3.68E-05	1.83E-04	0.132	459.0	6.38E-05

2.4.3.8 Seepage Velocity (ft/yr) and Flow Direction of Formation Water

This section discusses the natural seepage velocity and flow direction in the Mt. Simon sandstone. The predicted behavior of the injected CO_2 in the Mt. Simon sandstone is discussed in Section 5.

In northern Illinois and southern Wisconsin, groundwater flow in the Mt. Simon sandstone and other bedrock aquifers is fairly well understood. Several calibrated groundwater flow models have been developed by the Illinois State Water Survey (Meyer et al., 2009), the Wisconsin Geological and Natural History Survey (SWRPC & WGNHS, 2005) and the U.S. Geological Survey (Mandle and Kontis, 1992; Feinstein et al., 2010). However, groundwater flow in the deeper part of the Illinois Basin is not well understood because few wells penetrate deep formations such as the Mt. Simon Sandstone. However, based on limited field data and numerical modeling some information on groundwater flow is available. Within the Mt. Simon Sandstone, Bond (1972) determined that groundwater flows from west to east beneath the northern third of Illinois. Bond (1972) also noted that groundwater flows to the south in the deeper part of the Illinois Basin, but some data supporting this conclusion were questionable. Within the deeper part of the Illinois Basin, groundwater flow in the Mt. Simon Sandstone is generally very slow, on the order of inches per year (Cartwright, 1970; Gupta and Bair, 1997). Finally, Bond (1972) noted that groundwater flows upward from the Mt. Simon aquifer to the Ironton-Galesville in the Chicago area, where pumpage has lowered pressures in the Ironton-Galesville. The flow patterns described by Bond (1972) are generally consistent with those patterns described by Meyer et al. (2009) and Mandle and Kontis (1992).

Gupta and Bair (1997) used a steady-state, variable density, groundwater flow model to evaluate flow in the Mt. Simon Sandstone in the Midwest (Ohio, Indiana and parts of Illinois, Wisconsin, Michigan, Pennsylvania, West Virginia and Kentucky), including the eastern portion of the Illinois Basin. Results from this modeling indicated that flow in the shallow layers, such as in the Pennsylvanian bedrock, follows topographic-driving forces –recharge in upland areas and discharge in topographic lows such as river valleys. For deeper layers such as the Mt. Simon Sandstone, the flow patterns are influenced by the geologic structure with flow away from arches such as the Kankakee Arch and toward the deeper parts of the Illinois Basin (Figure 2-16). The model also indicated that groundwater flows upward from the Mt. Simon to the Eau Claire and downward from the Ironton-Galesville into the Eau Claire (Figure 2-17), but these vertical velocities are very small, <0.01 inches per year.

The modeling results of Gupta and Bair agree with results of Cartwright (1970). Cartwright (1970) estimated that 59,000 acre-ft of groundwater discharged from the Illinois Basin bedrock to streams. Cartwright (1970) also argued that 95% of this discharge flowed through vertical fractures in the Wabash valley fault zone and the Duquoin-Loudon anticlinal belt. These modeling results also agree with a hypothesis described by Bredehoeft et al. (1963) to explain the high brine concentrations (3 to 6 times higher than present seawater) found in some deep basins including the Illinois Basin. Bredehoeft et al. (1963) argued that confining layers such as the Eau Claire act as semi-permeable membranes, allowing water to pass out of permeable formations such as the Mt. Simon while retarding the passage of charged salt particles. The clay minerals in the confining layer have a net negative charge which retards the anions in the water. These anions then retard the movement of the cations (positive charge) via electrical attraction. This process happens very slowly, over geologic time periods of hundreds of thousands of years. The information presented above reflects our current understanding on groundwater flow in the Illinois Basin. This understanding is based on very limited data of which some is specific to the Mt. Simon but outside of the Illinois Basin. Intensive monitoring of the CO_2 plume during and after injection is expected to provide additional information.

Source:
Bond, D.C., 1972. Hydrodynamics in deep aquifer of the Illinois Basin, Illinois State Geological Survey Circular 470, Urbana, IL, 72 p.

Bredehoeft, J.D., C.R. Blyth, W.A. White and G.B. Maxey, 1963. Possible mechanism for concentration of brines in subsurface formations. Bulletin of the American Association of Petroleum Geologists 47(2): 257-269.

Cartwright, K., 1970. Groundwater discharge in the Illinois Basin as suggested by temperature anomalies: Water Resources Research, vol. 6, no. 3, p. 912-918.

Feinstein, D.T., R.J. Hunt and H.W. Reeves, 2010. Regional groundwater-flow model of the Lake Michigan Basin in support of Great Lakes Basin water availability and use studies, U.S. Geological Survey Scientific Investigations Report 2010-5109: 379.

Gupta, N., and E.S. Bair, 1997. Variable-density flow in the midcontinent basins and arches region of the United States, Water Resources Research, 33(8): 1785-1802.

Huang, T., and Rudnicki, J.W., 2006. A mathematical model for seepage of deeply buried groundwater under higher temperature and pressure, Journal of Hydrology, Vol. 327, 42-54.

Mandle, R.J., and A.L. Kontis, 1992. Simulation of regional ground-water flow in the Cambrian-Ordovician aquifer system in the northern Midwest, United States. Washington, D.C., U.S. Geological Survey Professional Paper 1405-C: 97.

Meyer, S.C., G.S. Roadcap, Y.-F. Lin and D.D. Walker, 2009. Kane County Water Resources Investigations: Simulation of Groundwater Flow in Kane County and Northeastern Illinois, Illinois State Water Survey Contract Report 2009-07: 425.

Southeastern Wisconsin Regional Planning Commission and Wisconsin Geological and Natural History Survey, 2005. A Regional Aquifer Simulation Model for Southeastern Wisconsin, Southeastern Wisconsin Regional Planning Commission Technical Report 41**:** 143.

Zimmerman, R.W., 1991. Compressibility of sandstones, Elsevier Publishing Co., Amsterdam.

2.4.4 Characteristics of Injection Zone Formation Water

Information on the injection zone formation water is primarily based on data obtained by the ISGS from the CCS #1 well installation (Frommelt, 2010). Fluid samples were collected from the CCS #1 open borehole after drilling and wireline geophysical testing were completed. Schlumberger's Modular Formation Dynamics Tester (MDT) and Quicksilver wireline equipment were run on April 28 and 29, 2009. The tool was used to collect formation pressure, formation temperature, and reservoir fluid samples at five depths (Table 2-4). The Quicksilver probe is designed to draw filtrate-contaminated fluid to the perimeter of the probe, where it is pumped into a flowline. This enables the probe center to discretely collect relatively high-quality reservoir fluid into a separate sampling flowline. The fluid properties (such as resistivity) in both flowlines are monitored in real time to control the independent pumping systems during sampling. Fluid sample volumes for the CCS#1 samples varied from 450 mL to 900 mL. These samples were analyzed by the Illinois State Water Survey.

Table 2-4. Data for fluid samples collected from the Mt. Simon sandstone in CCS#1 using the MDT sampler in April 2009

Sample ID	Sample Depth (feet)	Formation Pressure (psi)	Formation Temperature (°F)	TDS (mg/L)	Density (g/L)
MDT-4	5,772	2,582.9	119.8	164,500	1,089.7
MDT-3	6,764	3,077.5	125.1	185,600	1,120.7
MDT-14	6,764	3,077.5	125.1	179,800	Not analyzed
MDT-5	6,840	3,105.9	125.0	182,300	1,124.1
MDT-2	6,912	3,141.8	125.8	211,700	1,136.5
MDT-9	6,840	3,105.9	125.0	219,800	Not analyzed
MDT-1	7,045	3,206.1	125.7	228,100	1,123.5
MDT-8	7,045	3,206.1	125.7	201,500	Not analyzed

2.4.4.1 Temperature

Based on the MDT sampler (Table 2-4), formation temperatures ranged from 119.8°F (48.8 °C) at a depth of 5,772 feet to 125.8°F (52.1°C) at depth of 6,912 feet.

2.4.4.2 Pressure

The formation pressure measured with the MDT tool in CCS #1 (Table 2-4) varied with depth and had a minimum pressure of 2,583 psi recorded at 5,772 feet and a maximum pressure of 3,206 psi recorded at 7,045 feet.

2.4.4.3 Density

Based on five brine samples collected with the MDT sampler at the CCS #1 well, the fluid density ranged from 1,090 to 1,137 g/L, with an average of 1,119 g/L.

2.4.4.4 Viscosity

Dynamic viscosity is a function of brine temperature, salinity, and formation pressure. Viscosity increases with higher salinity and with lower temperatures. Viscosity slightly increases with higher formation pressure (Kestin et al., 1981). Kestin et al. (1981) studied the viscosity of NaCl brines.

Because the Mt. Simon brine is predominantly NaCl brine, using the method of Kestin et al. (1981) is appropriate. Using the data in Table 2-4, the brine viscosity for the Mt. Simon brine is estimated to range from 5.4×10^{-4} to 5.7×10^{-4} Pa sec with an average of 5.5×10^{-4} Pa sec.

Source:
Kestin, J., E. Khalifa and R.J. Correia, 1981. Tables of dynamic and kinematic viscosity of aqueous NaCl solutions in the temperature range 20-150°C and the pressure range 0.1-35 MPa. *Journal of Physical and Chemical Reference Data*, 10(1): 71-87.

2.4.4.5 Total Dissolved Solids

Salinity, expressed as TDS, also affects the injection capacity because it reduces the CO_2 solubility in water. Figure 2-18 illustrates the relative density of deep aquifer brines in the Illinois Basin. Figure 2-19 shows the broad distribution of TDS in the Mt. Simon which should exceed 60,000 mg/L over much of the Illinois Basin and 180,000 mg/L in the deeper portions of the basin. Figure 2-19 also shows the approximate position of the 20,000 mg/L TDS iso-concentration line for the Mt. Simon sandstone in the northern part of the state. South of this line, the groundwater is expected to exceed 20,000 mg/L TDS.

At the IBDP site, samples collected from CCS #1 varied with depth (Table 2-4), with TDS of 164,500 mg/L TDS at 5,772 feet and 228,100 mg/L TDS at 7,045 feet. The samples' average TDS is 190,000 mg/L . The proposed IL-ICCS site is within one mile of the CCS #1 well and similar concentrations of TDS are anticipated. Table 2-5 provides a summary (from IBDP wells) of TDS and ionic constituent data for Quaternary sands-and-gravel deposits and the Pennsylvanian-age Lower Mattoon sandstones (referred to asshallow groundwater), the Ironton-Galesville Sandstone, and Mt Simon Sandstone.

It is important to note that the values measured at the site are higher than those for the area shown in Figure 2-19. The contour values shown in Figure 2-19 were based on regional data and are not site specific. The data collected from the samples taken in CCS #1 provide the best estimate of what will be encountered at CCS #2. However, the overall regional trends are still described by Figure 2-19.

To provide additional information for formations which have not been sampled, salinity estimates were estimated based on open hole log resistivity and porosity data obtained in Verification Well #1. The salinity was estimated assuming 100% water saturation and then using a simplified Archie equation where apparent water resistivity calculation (RWA) equals resistivity multipled by porosity squared (RWA = Rt x phi^2) and then entering RWA and temperature and reading an equivalent NaCl salinity off Schlumberger's GEN-9 Log Interpretation Chart [Appendix N]. These values (Table 2-6) are in general agreement with the values in Table 2-5 (for formations which were sampled). Note that the salinity estimates using this technique can be skewed (to the low side) if resistivities are affected by fresh drilling mud or hydrocarbons.

Table 2-5: Fluid chemistry data for shallow groundwater, the Ironton-Galesville, and Mt Simon Formations.

Constituent	Shallow Groundwater	Ironton-Galesville	Mt. Simon
Conductivity (mS/cm)	1.5	80	170
TDS (mg/L)	1,000	65,600	190,000
Cl^- (mg/L)	170	36,900	120,000
Br^- (mg/L)	1	180	680
Alkalinity (mg/L)	380	130	80
Na^+ (mg/L)	140	17,200	50,000
Ca^{2+} (mg/L)	100	5,200	19,000
K^+ (mg/L)	1	520	1,700
Mg^{2+} (mg/L)	50	950	1,800
pH (units)	7.2	6.9	5.9

Table 2-6: Estimated Salinity from Verification Well #1 open hole resistivity and porosity logs using Schlumberger GEN-9 Log Interpretation Chart.

Formation	Depth Interval	Resistivity ohmm	Porosity (V/V)	RWA (RT * phi^2) ohmm	Temperature (DegF)	Salinity (per SLB GEN-9 chart using RWA and temperature) ppm
Chapel	444 to 450	16	0.10	0.16	65	45000
Renault	1284 to 1286	20	0.10	0.20	70	35000
St. Louis	1462 to 1478	3	0.24	0.17	71	30000
Borden	1606 to 1612	2.5	0.22	0.12	72	60000
Burlington-Keokuk Limestone	1850 to 1860	35	0.05	0.09	75	80000
Moccasin Springs	2254 to 2256	2	0.20	0.08	82	80000
Moccasin Springs	2540 to 2550	80	0.03	0.07	84	90000
Galena	2797 to 2800	600	0.02	0.24	87	25000
Galena	2808 to 2810	80	0.05	0.20	87	28000
Plateville	3094 to 3102	40	0.06	0.14	90	45000
St. Peter	3255 to 3265	11	0.23	0.58	92	8000
St. Peter	3305 to 3315	8.5	0.23	0.45	92	11000
St. Peter	3400 to 3410	11	0.20	0.44	93	12000
Ironton-Galesville	4903 to 4906	8.5	0.13	0.14	103	35000
Ironton-Galesville	5004 to 5008	8	0.10	0.08	103	65000
Eau Claire	5089 to 5091	80	0.03	0.07	104	75000
Mt. Simon	5559 to 5563	3.5	0.10	0.04	111	140000
Mt. Simon	5795 to 5800	2	0.13	0.03	113	190000
Mt. Simon	6032 to 6038	5.5	0.09	0.04	114	170000
Mt. Simon	6416 to 6418	1.8	0.18	0.06	118	80000
Mt. Simon	6841 to 6843	0.7	0.24	0.04	120	130000
Mt. Simon	6980 to 6990	0.8	0.23	0.04	120	130000

Source:
Leetaru, H.E., D.G. Morse, R. Bauer, S. Frailey, D. Keefer, D. Kolata, C. Korose, E. Mehnert, S. Rittenhouse, J. Drahovzal, S. Fisher, J. McBride, 2005. Saline reservoirs as a sequestration target, in An Assessment of Geological Carbon Sequestration Options in the Illinois Basin, Final Report for U.S. DOE Contract: DE-FC26-03NT41994, Principal Investigator: Robert Finley, p 253-324

2.4.4.6 Potentiometric Surface

Little information is available about the potentiometric surface in the Mt. Simon sandstone in Macon County because very few wells penetrate the Mt. Simon in central Illinois. The best available information regarding the potentiometric surface is discussed in Section 2.4.3.8 of this document.

Using the formation pressure (p) and fluid density (ρ) data in Table 2-4, the potentiometric head (b) was calculated using the relationship $p = \rho g h$, where g is the gravitational constant. The mean potentiometric head in the Mt. Simon has an elevation 249.5 feet MSL. If the well were filled with freshwater (ρ= 1,000 g/L), the potentiometric head would have an elevation of 996.1 feet MSL.

2.4.5 Additional or Alternative Zones Considered for Injection

No other geologic zones are being considered for CO2 injection at the IL-ICCS site.

2.5 Upper Confining Zone

Information on the upper confining zone, the Eau Claire Formation, is based on specific data obtained from the CCS #1 well installation (Frommelt, 2010) and is supplemented by regional geologic information from previous ISGS studies and reports. In order for a saline reservoir to be used for injection of CO_2, there must be an effective hydrologic seal that restricts upward fluid movement. Within the Illinois Basin, three thick and wide-spread shale units function as major regional seals. These units are the Cambrian-age Eau Claire Formation, the Ordovician-age Maquoketa Formation, and the Devonian-age New Albany Shale (Figure 2-8). The Eau Claire Formation has no known penetrations (with the exception of the IBDP injection and verification wells) within a 17-mile radius surrounding the proposed IL-ICCS site; therefore, integrity of the upper confining zone is not an issue.

Gas storage projects in the Illinois Basin confirm that the Eau Claire is an effective seal in the northern and central portions of the Basin. Core analysis data from the Manlove Gas Storage Field (Larson, 1965), 37 miles to the northeast of the proposed site, show that the Eau Claire shale intervals have vertical permeability values of less than 0.1 mD.

A diagrammatic north-south cross section of the Basin through the central part of Illinois (Figure 2-20) shows that the Eau Claire Formation, the primary seal, has a laterally persistent shale interval above the Mt. Simon and is expected to provide an excellent seal.

Wireline logs from the CCS #1 well and two geologic cross sections near the proposed site (Figures 2-6 and 2-7) indicate that at the IL-ICCS site, there should be about 500 feet of Eau Claire Formation directly above the Mt. Simon Sandstone.

Source:

Larson, K.R., 1965. Exhibit 25: Core Analyses. In the matter of the Application of the Peoples Gas Light and Coke Company for an order and certificate of convenience and necessity to develop, construct, operate and maintain the Mahomet Storage Field in Champaign and Piatt Counties, Illinois Commerce Commission, Docket No. 51416 [Unpublished data, a copy of which is available for inspection at the Library of the Illinois State Geological Survey, Champaign IL].

2.5.1 Geologic Name(s) of Confining Zone

The primary confining zone (seal) is the Cambrian-age Eau Claire Formation. Based on the data from CCS #1, the Eau Claire has a total thickness of 497.5 feet. The shale section of the Eau Claire has a thickness of 198.1 feet and is the lowermost section within the formation.

2.5.2 Depth Interval of Upper Confining Zone Beneath Land Surface

At CCS #1, the Eau Claire Formation occurs at a depth of 5,047 feet to 5,545 feet below ground surface. The shale section of the Eau Claire occurs at a depth of 5,347 to 5,545 feet.

2.5.3 Characteristics of Confining Zone

2.5.3.1 Lithologic Description

The Cambrian-age Eau Claire Formation is composed primarily of a sandstone, sandy dolomite, and sandy dolomitic siltstone in northern Illinois (Figure 2-8), but shale and siltstone components are more dominant in the central part of the Illinois Basin (Willman et al., 1975). In the southern part of the basin, the Eau Claire is a mixture of dolomite and limestone with some fine-grained siliciclastics.

In the CCS #1 well, the Eau Claire Formation consists of 198 feet of shale (5,347 to 5,545 feet) overlain by 300 feet (5,047 to 5,347 feet) of very-fine grained limestone interbedded with thin siltstone layers. Bell et al. (1964) provided a detailed description of a sample study of the Eau Claire Formation from the Weaber-Horn #1 well, 51 miles to the south, where the formation is 580 feet thick. In this well, the Eau Claire consists of, in descending order, 247 feet of dolomitic limestone, 83 feet of dolomitic siltstone and dolomitic shale, 75 feet of dolomite, 120 feet of sandy siltstone and silty, fine-grained sandstone, 10 feet of dolomite, and 45 feet of argillaceous siltstone and shale. To compare it with the Eau Claire in ADM CCS #1, the formation in the Weaber-Horn #1 consists of 405 feet of carbonate strata overlying 175 feet of fine-grained clastic strata. The shale component, however, much more prominent in ADM CCS #1, where it comprises the lower 198 feet. Within Weaber-Horn #1, the shale component is subordinate to the thicker silty sandstones and siltstones. In summary, within about 50 miles to the south, the lower portion of the Eau Claire lithologically coarsens with shale decreasing and siltstone and very fine-grained sandstone increasing. The upper portion of the Eau Claire lithologically to the south remains dominated by carbonate strata but a very fine-grained clastic interval appears in the mid-section of the upper part of the formation.

From limited x-ray diffraction data, the mineralogy of the shale is 60 percent clay minerals and 37 percent quartz and potassium feldspar. The shale is laminated and dark gray to black in color.

Source:

Bell, A.H., E. Atherton, T.C. Buschbach, D.H. Swann, 1964. Deep Oil Possibilities of the Illinois Basin, Illinois State Geological Survey, Circular 368, 38 p.

Willman, H.B., E. Atherton, T.C. Buschbach, C. Collinson, J.C. Frye, M.E. Hopkins, J.A. Lineback, and J.A. Simon, 1975. Handbook of Illinois Stratigraphy, Illinois State Geological Survey Bulletin 95, 261 pp.

2.5.3.2 Geomechanical Data

Geomechanical data were collected by lab and field testing. Lab testing was used to determine elastic parameters for a single Eau Claire shale sample. Field testing, a mini-frac test, was conducted to determine the in situ fracture pressure.

An Eau Claire shale sample was collected from CCS #1 at a depth of 5,478.5 feet. This sample was tested by Weatherford Labs (Houston, TX) and has the following properties—Young's modulus of $5.50x10^6$ psi, Poisson's ratio of 0.27, bulk modulus of $3.92x10^6$ and shear modulus of $2.17x10^6$ psi.

"Mini-frac" testing was conducted within the Eau Claire to determine the effectiveness of the shale as a caprock seal (Frommelt, 2010). Mini-fracs are very small volume tests that inject fluid up to the parting pressure of the injection zone.

A mini-frac test using Schlumberger's Modular Dynamics Testing tool was conducted across a 2.8-foot shale interval of the Eau Claire, centered at a depth of 5,435 feet. The test was designed for four short-term injection/falloff test periods (15 to 60 minutes in duration). The fracture pressure from these four tests ranged from 5,078 to 5,324 psig, corresponding to a fracture gradient ranging from 0.93 to 0.98 psi/ft in the Eau Claire shale.

2.5.3.3 Intrinsic Permeability

None of the CCS #1 sidewall rotary core plugs penetrated shale. From the whole core collected from the Eau Claire, none of the individual shale layers at the inch to centimenter scale were thick enough for obtaining a core plug for permeability analyses. The shale dominated portion of the whole core parted horizontally in very small increments such that drilling horizontal plugs and vertical plugs was not possible. No permeability tests were done on shale samples from cuttings.

Within the upper confining interval of 5,047 to 5,545 feet, 12 Eau Claire plugs were available for porosity and permeability testing. The plugs are described as very fine grained sandstones, microcrystalline limestone, and siltstone. Because sidewall rotary core plugs are taken horizontally, the permeability data from these plugs indicate the horizontal (not vertical) permeability. The average horizontal permeability for the 12 sidewall rotary core plugs is 0.000344 mD.

The average vertical permeability for the upper confining shale layer is expected to be much lower than 0.000344 mD because this value is based on the non-shale horizontal permeability values. Vertical permeability on plugs is generally lower than horizontal permeability and shale permeability is generally much lower than sandstone, limestone, and siltstone.

The Illinois State Geological Survey database of UIC wells with core from the Eau Claire was also used to characterize the upper confining seal. This database shows that the Eau Claire's median permeability is 0.000026 mD and median porosity is 4.7%. At the Ancona Gas Storage Field, located approximately 80 miles to the north of the proposed IL-ICCS site, cores were obtained through 414 feet of the Eau Claire, and 110 analyses were performed on a foot-by-foot basis on the recovered core. Most vertical permeability analyses showed values of <0.001 to 0.001 mD. Only five analyses were in the range of 0.100 to 0.871 mD, the latter being the maximum value in the data set. This indicates that even the more permeable beds in the Eau Claire Formation are expected to be relatively tight and tend to act as sealing lithologies.

Source:
Illinois State Geological Survey Mt. Simon database

2.5.3.4 Hydraulic Conductivity

Intrinsic permeability (k) and hydraulic conductivity (K) are related according to the following equation (Freeze and Cherry, 1979):

$$K = k \rho g / \mu$$

where ρ = fluid density
g = gravitational acceleration
μ = dynamic viscosity

Intrinsic permeability (k) is a property of the rock, while hydraulic conductivity (K) includes properties of the rock and fluid. Because fluid samples were not collected from the Eau Claire, the properties of the fluid properties of CCS #1 sample MDT-4 (Table 2-4), which is the Mt. Simon brine sample collected closest to the Eau Claire, were used for these calculations. Its measured properties include temperature of 119.8°F and density of 1,089.7 g/L. Its dynamic viscosity was estimated to be 758.0 μPa sec. For an intrinsic permeability value of 0.000344 mD, the hydraulic conductivity equals 4.8×10^{-10} cm/sec.

Source:
Freeze, R.A. and J.A. Cherry, 1979. *Groundwater*. Englewood Cliffs, N.J., Prentice-Hall, Inc.

2.5.3.5 Alternative Confining Zones Proposed, Include Explanation and Depth Interval(s)

Secondary seals provide additional backup containment of the CO_2 should an unlikely failure of the primary seal occur. Secondary seals listed here are units with low permeability that are regionally present and serve as confining seals for oil, gas and gas storage fields throughout Illinois where they are present.

Study of the wireline logs of the CCS #1 well and regional studies indicate that there are two laterally continuous, secondary seals at the IL-ICCS site (Frommelt, 2010). The Ordovician-age Maquoketa Shale is 206 feet thick at the CCS #1 well site with the top at a depth of 2,611 feet below Kelly Bushing (KB). Kelly Bushing is defined as ground level plus 15 feet. This shale is a regional seal for hydrocarbon production from the Ordovician Galena (Trenton) Limestone. The top of the Devonian-Mississippian-age New Albany Shale (Figure 2-21) is at a depth of 2,088 feet and is about 126 feet thick at the CCS #1 well site. Extensive data from oil fields through the Illinois Basin shows that this shale is an excellent seal for hydrocarbons; hence, it should also be an excellent secondary seal against the vertical migration of CO_2 at this site.

There are also many minor, thinner Mississippian- and Pennsylvanian-age shale beds that will also form seals against CO_2 vertical migration.

2.6 Lower Confining Zone

Information on the lower confining zone (Precambrian granite) is based on the specific data obtained from the CCS #1 well installation (Frommelt, 2010).

Because the lower confining zone is the basement granite and no other sedimentary rocks are below the granite, no data will be collected on the granite for the ICCS project. The fracture pressure, porosity, and permeability of the granite will not impact injection or fluid migration as the CO_2 injection interval will almost certainly be above this interval and the CO_2 is expected to move upward away from the granite.

2.6.1 Geologic Name(s) of Confining Zone

The lower confining zone is the Precambrian granite basement.

2.6.2 Depth Interval of Lower Confining Zone Beneath

At CCS #1, the top of the Precambrian granite is at a depth of 7,165 feet, which indicates that the base of the Mt. Simon in the IL-ICCS injection well will be at a similar depth.

2.6.3 Characteristics of Confining Zone

2.6.3.1 Lithologic Description

The Precambrian-age rock in the Illinois Basin is composed of a medium- to coarse-grained granite or rhyolite and is between 1.1 to 1.4 billion years old (Bickford et al., 1986).

Source:
Bickford, M.E., W.R. Van Schmus, and I. Zietz, 1986. Proterozoic history of the mid-continent region of North America: Geology, vol. 14, no. 6, pp. 492–496.

2.6.3.2 Fracture Pressure at Depth

The ISGS could not find any data on fracture pressure of granites in Illinois. No tests were conducted at the IBDP injection or verification wells to determine the fracture pressure of the lower confining zone. The fracture pressure of the granite is not anticipated to have any effect on the injection or storage of CO_2 in the overlying Mt. Simon Sandstone.

2.6.3.3 Intrinsic Permeability

The top of the granite occurs at depth of 7,165 feet. A total of 65 feet of granite was drilled at CCS #1. At 7,200 feet, one sidewall core plug was collected; the permeability was determined to be 0.0091 mD.

2.6.3.4 Hydraulic Conductivity

Using the pressure and fluid properties obtained for MDT-1 (Table 2-4), hydraulic conductivity for the granite is estimated to be 1.8×10^{-8} cm/sec.

2.6.3.5 Alternative Confining Zones Propose

There are no alternative lower confining zones since no wells in Illinois have found anything else but the Precambrian granite basement below the Mt. Simon Sandstone.

2.7 Overlying Sources of Groundwater at the Site.

To determine the lowermost underground source of drinking water (USDW) at the site, extensive field investigations were undertaken. Field investigations included coring from a depth of 146 to 504 feet, running several geophysical logs, packer testing seven intervals to find rock with sufficient permeability for groundwater monitoring, and limited borehole sampling to evaluate water quality. Pennsylvanian bedrock was recovered from this borehole and included fine-grained sandstone, limestone, siltstone, shale and some coal. None of the rock appeared to be capable of producing much water. Details about these field investigations can be found in letter from Dean Frommelt of ADM to Illinois EPA, dated September 29, 2009 (Frommelt, 2009) [Appendix H]. In summary, shallow Pennsylvanian sandstones (e.g., the lower Bond Formation sandstone or Lower Mattoon sandstones) produced groundwater with TDS values less than 10,000 mg/L and the Inglefield Sandstone produced groundwater with TDS values greater than 10,000 mg/L. In a December 2, 2009 letter (Nightingale, 2009), the Illinois EPA approved the Pennsylvanian bedrock as the lowermost USDW in the vicinity of the ADM site (e.g.,the IBDP site) [Appendix H]. As the IBDP site is located less than one mile from the proposed IL-ICCS project site, it is assumed that the Pennsylvanian bedrock would also be determined as the lowermost USDW at the IL-ICCS site.

Recent water quality sampling at the site is consistent with these field investigations. Samples were collected from a monitoring well (MMV-04B) screened at depths of 275 to 295 feet. Samples from this well were collected from August 2009 through July 2011 and have an average of 18,471 mg/L TDS and range from 8,575 to 28,629 mg/L TDS. Meanwhile, four wells installed for the Class I UIC permit (wells G101-G104, screened at depths of 130 to 140 feet) indicate that this shallower groundwater has an average TDS of 1,151 mg/L.

Source:

Frommelt, D. 2009. Letter to Illinois Environmental Protection Agency, Subject: Lowermost underground source of drinking water (USDW), Archer Daniels Midland Company – UIC Permit UIC-012-ADM, dated September 29, 2009. [Appendix H]

Nightingale, S. 2009. Letter to Archer Daniels Midland Company, Subject: Lowermost underground source of drinking water (USDW), Permit No. UIC-012-ADM, Log No. PS09-206, dated December 2, 2009. [Appendix H]

2.7.1 Characteristics of the Aquifer Immediately Overlying the Confining Zone

2.7.1.1 Elevation at Top of Aquifer

The first aquifer overlying the Eau Claire Formation (the primary seal for the Mt. Simon Sandstone) which contains salt water at the proposed location is the Cambrian–age Ironton-Galesville Formation (Figure 2-8). Based on the geophysical logging in CCS #1, the Ironton-Galesville was found at depths of 4,928 to 5,047 feet (119 feet thick) (Frommelt, 2010). Based on the geophysical logging in Verification Well #1, the Ironton-Galesville was found at depths of 4,901 to 5012 feet (111 feet thick). This thickness range corresponds with regional mapping of the Ironton-Galesville formation that shows it to be between 100 and 150 feet thick at the CCS#2 site (Figure 2-22).

2.7.1.2 Potentiometric Surface

Little information is available about the potentiometric surface in the Ironton-Galesville Formation in Macon County because very few wells penetrate the Ironton-Galesville in central Illinois. Recently obtained data at IBDP Verification Well #1 finds the Ironton-Galesville to have a pressure of 2,073 psi at a depth of 4,918 ft. Assuming the well is filled with freshwater, this pressure equates to an elevation of 550.9 feet, which is approximately 133.1 feet below ground surface.

2.7.1.3 Total Dissolved Solids

Regional mapping of the formation by the USGS shows that the proposed IL-ICCS injection well should encounter saline waters (Figure 2-23) in this interval. Recently obtained data at IBDP - Verification Well #1 from the Ironton-Galesville found TDS to be 65,600 mg/L. Water quality data collected from IBDP CCS #1 were previously discussed in section 2.4.4.5.

2.7.1.4 Lithology

The Ironton and Galesville Sandstones are considered as a single undifferentiated sandstone unit in this report for two reasons. Both units are not exposed in Illinois and the contact between the units cannot be recognized in many of the borings through the units (Buschbach, 1964). Buschbach noted that the two sandstones are difficult to differentiate without a “good” set of well samples. Since the contact between the two formations is primarily based on grain-size (Emrich, 1966), the contact also is difficult to recognize on wireline logs. In addition, the Ironton-Galesville Sandstone constitutes a widespread aquifer in the northern Illinois and southern Wisconsin and has been traced to about 20 miles south of Macon County (Emrich, 1966). Emrich provided descriptions of both sandstones from the subsurface of northern Illinois:

the Ironton is a relatively poorly sorted, fine- to coarse-grained, dolomitic sandstone, whereas the Galesville is a sandstone that is relatively better sorted, finer grained, and "cleaner" than the overlying Ironton. The CCS #1 well and Verification Well #1 are the only wells that penetrated this interval within a 17-mile radius of the proposed site. No lithologic data for the Ironton-Galesville were collected during the drilling of these wells.

Sources:
Buschbach, T.C., 1964. Cambrian and Ordovician Strata of Northeastern Illinois, Illinois State Geological Survey, Report of Investigations 218, 90 p.
Emrich, G.H., 1966. Ironton and Galesville (Cambrian) Sandstones in Illinois and adjacent areas, Illinois State Geological Survey, Circular 403, 55 p.

2.7.1.5 Aquifer Thickness

Based on the geophysical logging in CCS #1, the Ironton-Galesville was found to be 119 feet thick.

2.7.1.6 Specific Gravity

Little information was available about the specific gravity of fluids in the Ironton-Galesville Formation in Macon County because very few wells penetrate the Ironton-Galesville in central Illinois. No water quality data were for the Ironton-Galesville were collected during the drilling of CCS #1 for the Ironton-Galesville. New data (2011) from IBDP Verification Well #1 found the specific gravity of swab samples from Perforated Zone 10 (5001') and Perforated Zone 11 (4918') was 1.046 and 1.043 g/cc, respectively.

2.7.2 Underground Sources of Drinking Water

2.7.2.1 Maps and Cross Sections

Maps and Cross-sections/ Quaternary Deposits

Sand and gravel aquifers are found in the Quaternary (Pleistocene and recent) geologic deposits (Figure 2-24). Larson et al. (2003) described these deposits for DeWitt, Piatt, and northern Macon Counties. While the water quality of groundwater in these aquifers is not known precisely, these aquifers are used for water supplies and are considered to be underground sources of drinking water.

The vertical sequence of sand and gravel aquifers in the IL-ICCS site area is illustrated in Figure 2-25. Thin sand and gravel aquifers may be present within the Banner Formation (Figure 2-27), the lower portion of the Glasford Formation (Figure 2-28), and the Tiskilwa Formation (Figure 2-29). Somewhat thicker sand and gravel aquifers (5 to 20 feet thick) may occur in the upper portion of the Glasford Formation (Figure 2-30) and are likely found within 100 feet of the ground surface. The Mahomet aquifer, a major regional aquifer that occurs in part of Macon County, is not located beneath the IL-ICCS site (Figure 2-26), but is present approximately 5 miles to the north.

Maps and Cross-sections/ Pennsylvanian Bedrock

The uppermost bedrock at the site is Pennsylvanian-age bedrock (Figure 2-31). For the Illinois Department of Natural Resources, Office of Mines and Minerals (IDNR-OMM), the ISGS previously produced county-wide cross-sections to help IDNR-OMM determine the depth of oil-field casing needed to protect underground sources of drinking water (USDW). A cross-section was produced for Christian and Macon Counties, as shown in Figures 2-32 & 2-33 (Vaiden, 1991). These cross-sections were developed using water quality data from the ISWS and estimates from geophysical logs using the technique of Poole et al. (1989). The source of the water quality data is noted on the cross-section. This cross-section indicates that the water quality in the uppermost Pennsylvanian bedrock is less than 10,000 mg/L, but the TDS rapidly increases below the No. 2 Coal (Figures 2-32, 2-33 & 2-34) and generally exceeds 10,000 mg/L.

Maps and Cross-sections/Mississippian Bedrock

Because water quality data for the Mississippian bedrock is not available at the site or in Macon County, regional data are the only source for this data. Brower et al. (1989) noted that mineralization of groundwater in the Valmeyeran and Chesterian units of the Mississippian System was low in outcrops (and in subcrops beneath Quaternary strata) and reached a maximum of 100,000 to 160,000 mg/L TDS in the deep subsurface in Illinois Basin (Figure 2-34). There are no Mississippian unit outcrop/subcrop areas in Macon County. Figure 2-34 shows the estimated position at which 10,000 mg/L TDS groundwater is encountered in the Valmeyeran and Chesterian, respectively. It is not expected that Mississippian-age strata at the proposed injection site will be a USDW.

Source:

Brower, R. D., A. P. Visocky, I. G. Krapac, B. R. Hensel, G. R. Peyton, J. S. Nealon and M. Guthrie, 1989. Evaluation of underground injection of industrial waste in Illinois, Illinois Scientific Surveys Joint Report 2: 89.

Larson, D.R., B.L. Herzog and T.H. Larson, 2003. Groundwater Geology of DeWitt, Piatt, and Northern Macon Counties, Illinois. Champaign, IL, Illinois State Geological Survey Environmental Geology 155: 35.

Poole, V.L., K. Cartwright and D. Leap, 1989. Use of Geophysical Logs to Estimate Water-Quality of Basal Pennsylvanian Sandstones, Southwestern Illinois. Ground Water 27(5): 682-688.

Vaiden, R.C., 1991. Cross-Section E-E', Christian and Macon Counties. Unpublished cross section throughout oil producing areas of Illinois, used to estimate total dissolved solids in certain sandstones. Champaign, IL, Illinois State Geological Survey.

2.7.2.2 Lowest Depth of Underground Source of Drinking Water (USDW)

The Pennsylvanian bedrock is anticipated to be the lowermost USDW at the IL-ICCS project site. The depth of the lowermost USDW is expected to be similar to the depths found at the IBDP site compliance wells, or approximately 140 feet below the ground surface.

Source: Quarterly Groundwater Report For Illinois EPA Underground Injection Control Permit Number UIC-012-ADM (2010 Q4), Locke, R. and Mehnert, E. December 17, 2010.

2.7.2.3 Elevation of Potentiometric Surface of Lowest USDW Referenced to Mean Sea Level

The potentiometric surface of lowest USDW is expected to be approximately 55 to 59 feet below the ground surface, based on potentiometric data collected from the four groundwater compliance monitoring wells at the IBDP site during the 4th quarter of 2010 (Locke and Mehnert, 2010). The potentiometric surface of the lowermost USDW is anticipated to be approximately 620 feet above MSL at the IL-ICCS project site.

Source:

Locke, R. A. II, and Mehnert, E., December 17, 2010. Quarterly Groundwater Report For Illinois EPA Underground Injection Control Permit Number UIC-012-ADM (2010 Q4) submitted by the Illinois State Geological Survey to Mark Carroll, Environmental Compliance Manager, ADM Decatur Corn Processing Plant.

2.7.2.4 Distance to Nearest Water Supply Well

Water well records were found in the Illinois State Water Survey database for three private water supply wells located in the southeast quarter of Section 32 (**Figure 2-35**). These wells are likely to be located within ¼ to ½ mile of the injection well. These wells are described in Table 2-7.

Table 2-7: Description of nearest potable water wells in Section 32, T17N, R3E

API #	Well Owner	Well Depth (ft)	Well Diameter (in)	Year Drilled
121152203900	Gary Sebens	55	36	1988
121152221200	Gary Sebens	38	36	1990
121152283500	Anna Stiles	56	36	1992

2.7.2.5 Distance to Nearest Downgradient Water Supply Well

The wells described above are likely to be the closest wells downgradient from the injection well. Shallow groundwater likely flows to the south and east, which is the same direction that the land surface slopes (toward Lake Decatur).

2.8 Minerals and Hydrocarbons

2.8.1 Mineral or Natural Resources beneath or within 5 miles of the Site

2.8.1.1 Stone, Sand, Clay and Gravel

Sand and gravel resources are commonly present in the low terraces and floodplain of the Sangamon River and its tributaries. Several sand and gravel pits have operated in the area in the past and currently there are one active and two idle operations in or near the project area. The nearest active sand and gravel pit is approximately 12 miles to the west-southwest of the ADM site. Relatively thick limestone deposits, suitable for construction aggregates, generally occur at depths greater than 1,100 feet. Access to these limestones is possible only through underground mining methods, which is not economically feasible at the present time.

Source:

Hester, N.C., 1969. Sand and gravel resources of Macon County, Illinois: Illinois State Geological Survey Circular 446, 16 p.

Lamar, J.E., 1964. Subsurface limestone resources in Macon County: Illinois State Geological Survey Unpublished Manuscript 141

2.8.1.2 Coal

The nearest active coal mines are the Viper Mine (about 35 miles west-northwest in Logan County) and Crown III Mine (operated by Springfield Coal Company, about 65 miles southwest in Macoupin County).

The nearest historical coal mining on record at the ISGS were the three mines in Decatur. The closest (Figure 2-36) is within 5 miles of the proposed site, the Decatur No. 1 Mine. The shaft for this mine was northeast of the intersection of Eldorado and Jefferson Streets in Decatur (about 3 miles southwest of the site), and was about 600 feet deep. This longwall mine has no surviving map of the workings, but the main haulage entry was shown on the adjacent mine map, Macon County No. 2 Mine, which was connected underground. The Decatur No. 1 Mine operated from 1879 until 1914. The reported production was 1,780,000 tons, which would have undermined about 475 acres. The adjacent Macon County No. 2 Mine produced 2,660,000 tons, and undermined 430 acres. The portions of the only surviving map indicate that these mines operated west of Illinois Route 47/121. The third mine in Decatur is farther southwest, near the intersection of US Route 51 and Cantrell Street in Decatur. The Macon County No. 1 Mine operated from 1903 until 1947 and produced 4,590,000 tons. This production undermined over 670 acres. All of these mines recovered the Springfield Coal, which is between 4.0 and 5.0 feet thick in this area.

The presence of other unlocated or unrecorded old coal mines is unlikely. The first recorded coal exploration was in 1875, but coal was not found until 1876, on the third test hole. The great depth to the coal prevented small operators from opening the local mines that prevailed in many other counties.

Source:
Chenoweth, C., and A. Louchios, 2004. Directory of Coal Mines in Illinois, 7.5-minute Quadrangle Series: Decatur Quadrangle, Macon County, Illinois. Illinois State Geological Survey, 12 p., with “Coal Mines in Illinois – Decatur Quadrangle, Macon County, Illinois”, Illinois State Geological Survey Maps (1:24,000).

Illinois State Geological Survey, 2006. Directory of Coal Mines in Illinois, Logan County, 10 p.

Illinois State Geological Survey, 2006. Directory of Coal Mines in Illinois, Macoupin County, 17 p.

Existing Mineral Resources Near IL-ICCS Site location: Sec 32, T 17N, R E

A review of the known coal geology within a five mile radius of the proposed drilling site indicates that although several high-sulfur coals are present throughout the area, only the Springfield coal has a thickness of between 42 and 66 inches, which is considered mineable. Mining is restricted today due to urbanization and commercial development at the surface.

This restriction extends to five miles in all directions except to the north, north-east and east, where the coal is technically “available” for mining. “Available” coal means that the coal is not known to have geological, technological or land-use restrictions that would negatively impact the economics or safety of mining. These resources are not necessarily economically mineable at the present time, but they are expected to have mining conditions comparable with those currently being mined in the state. The top of the Springfield coal in the CCS #1 well is at a depth of 647 feet and its thickness, based on geophysical log analysis, is about 4 to 5 feet thick. In general, the coal bed dips gently eastward as the depth of the coal ranges from 500 feet deep five miles west of the site, to 725 feet deep five miles east of the site. Price, depth and coal thickness are inter-related economic factors that determine if coal might be mined in the future. Prior to 1947, there was mining in this seam over 3 miles to the southwest from the site, where it is thicker.

Source: ISGS County Coal Map Data, Macon County, Illinois: available on the ISGS Coal Section website at: http://www.isgs.uiuc.edu/maps-data-pub/coal-maps/counties/macon.shtml

Treworgy, C., C. Korose, C. Chenoweth, and D. North, 2000. Availability of the Springfield Coal for Mining in Illinois, Illinois State Geological Survey, Illinois Minerals 118.

<u>2.8.1.3 Oil and Gas</u>

Oil and natural gas have been produced from both oil fields and solitary wells in the area of interest. The largest of these oil fields is the Forsyth Field, part of which is northwest of the IL-ICCS Site (Figure 2-36). The field produces from Silurian strata between depths of about of 2,070 and 2,200 feet. The producing zone is usually about 10 feet thick, but zones up to 60 feet thick have been recorded. In 2008, 6,100 barrels (bbls) of oil were produced from 48 producing wells. The total production for the field is 650,100 bbls of oil, as of the end of 2008.

The next nearest oil field in the area of interest is the Oakley Field, the western edge of which is located about 3.5 miles east from the ADM ICCS Site. The field produces from Devonian strata between depths of about of 2,255 and 2,310 feet. The producing zone is usually about 5 to 25 feet thick. In 2008, 1,200 bbls of oil were produced from 2 producing wells. The total production for the field is 43,100 bbls of oil, as of the end of 2008.

The third oil field in the area of interest is the Decatur Field, the eastern edge of which is located less than 6 miles west of the ADM ICCS Site. The field produces from Silurian strata between depths of about of 2,000 and 2,500 feet. The producing zone is usually about 10 to 20 feet thick. In 2008, 400 bbls of oil were produced from 9 producing wells. The total production for the field is 49,900 bbls of oil, as of the end of 2008.

In addition, there is a single oil well “field,” Decatur North, located about 1 mile north of the proposed injection well site. The well produced 125 barrels from Silurian strata at a depth of 2,220 to 2,224 feet. This well was plugged and abandoned in late 1954 after eight months of production.

There is also a single production well, now plugged, that is located about 2 miles to the west of the ADM ICCS Site. The well was drilled in 1984 and abandoned in 1993. The well production was from Silurian strata at depths of about 2,040 to 2,050 feet. The total production for the well is about 2,200 bbls.

Natural gas is produced from several wells in the area that were drilled primarily for water. The gas is produced from Pleistocene sediments at depths of about 80 to110 feet deep. The gas is suitable for domestic or agricultural usage but not for commercial development as a natural gas field.

Source:

Various years, Illinois Annual Oil Field Reports, Illinois State Geological Survey.

ISGS ILWATER database available at: http://www.isgs.uiuc.edu/maps-data-pub/wwdb/launchims.shtml

2.9 References cited in the figures

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Leetaru, H., 2011. Personal communication, Illinois State Geological Survey.

Kolata, D.R., 2005. Bedrock Geology of Illinois, Illinois State Geological Survey Illinois Map 14: 1:500,000.

Larson, D.R., B.L. Herzog and T.H. Larson, 2003. Groundwater Geology of DeWitt, Piatt, and Northern Macon Counties, Illinois. Champaign, IL, Illinois State Geological Survey Environmental Geology 155: 35.

Loyd, O,B. and W.L. Lyke, 1995. Ground Water Atlas of the United States, Segment 10: Illinois, Indiana, Kentucky, Ohio and Tennessee, United States Geological Survey Hydrologic Investigations Atlas 730-K, 30 p

Willman, H.B., E. Atherton, T.C. Buschbach, C. Collinson, J.C. Frye, M.E. Hopkins, J.A. Lineback, and J.A. Simon, 1975. Handbook of Illinois Stratigraphy, Illinois State Geological Survey Bulletin 95, 261 pp.

V. Smith, personal communication, Schlumberger Carbon Services, 2011

Figure 2-1: Regional structure map showing no regional structures within a 15-mile radius of the ADM Plant near Decatur, Macon County. Source: Illinois State Geological Survey.

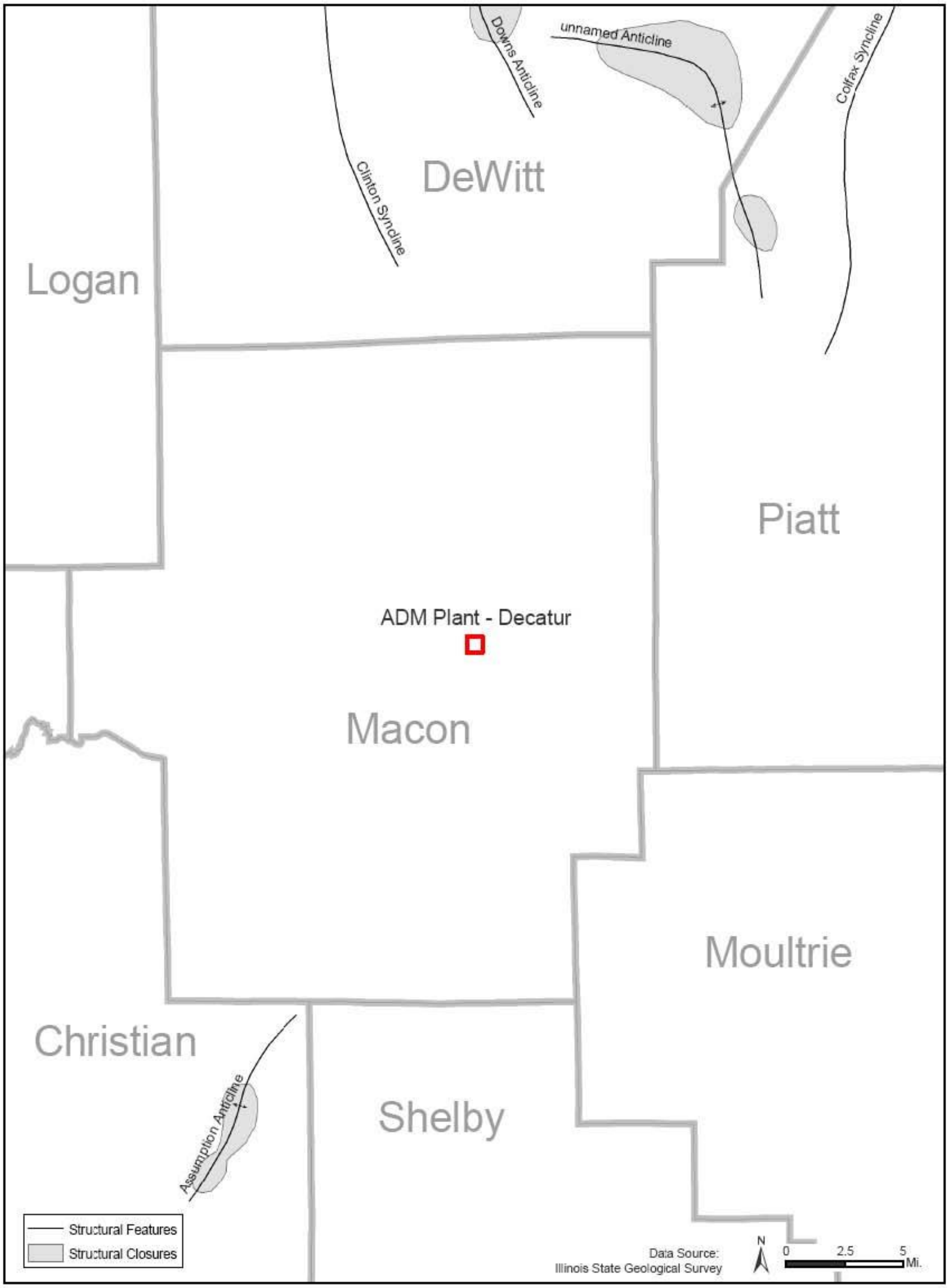


Figure 2-2: Aerial photo over the proposed injection site (IL-ICCS well location labeled). The yellow lines denote seismic lines that were recorded. Reference Figures 2-3 and 2-4 for corresponding geologic cross-sections. Source: Byers, ISGS, 2011

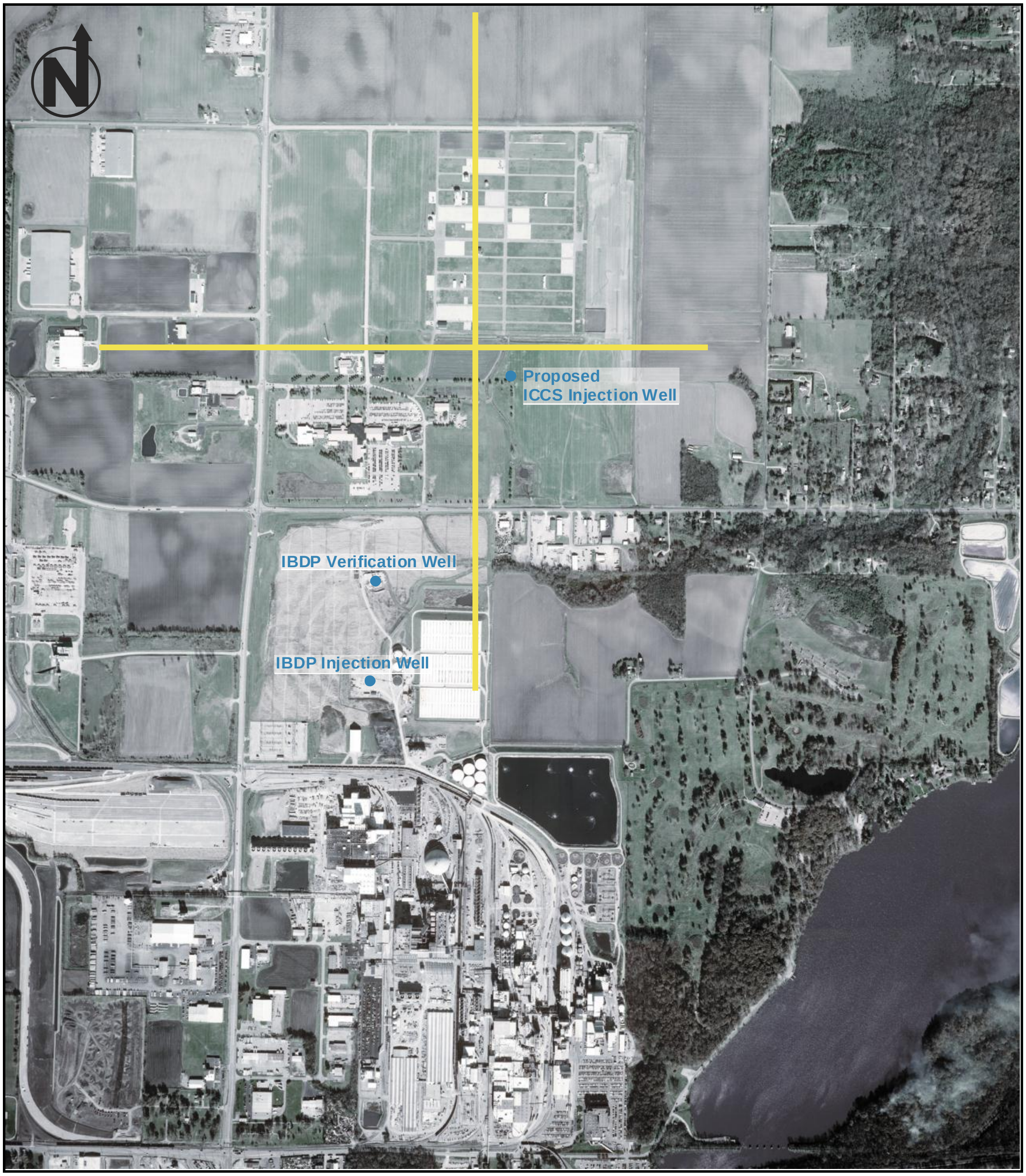


Figure 2-3: East-West seismic reflection profile along the proposed IL-ICCS injection site. Source: Leetaru, 2011

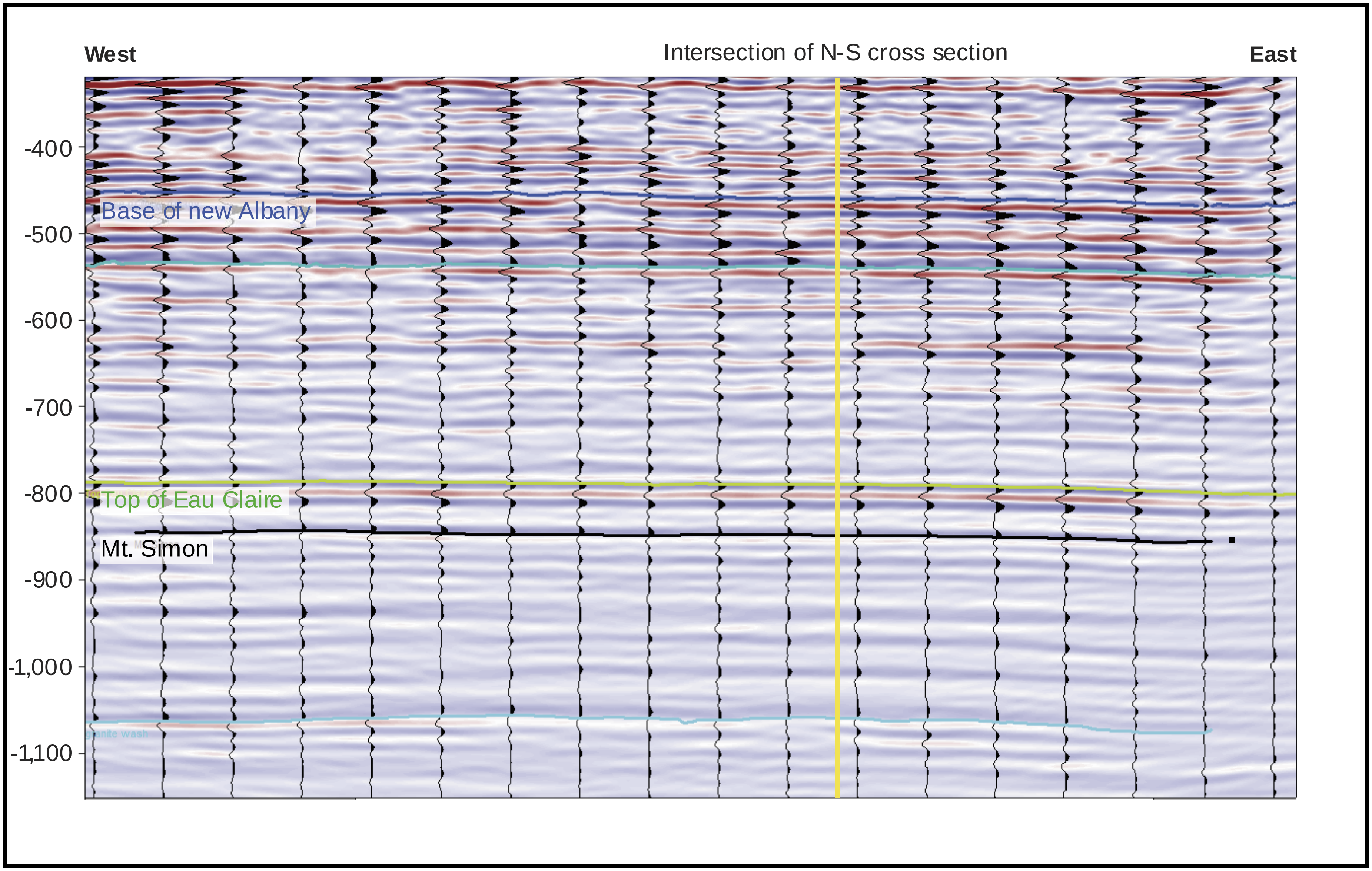


Figure 2-4: North-South seismic reflection profile along the proposed IL-ICCS injection site. Source: Leetaru, 2011

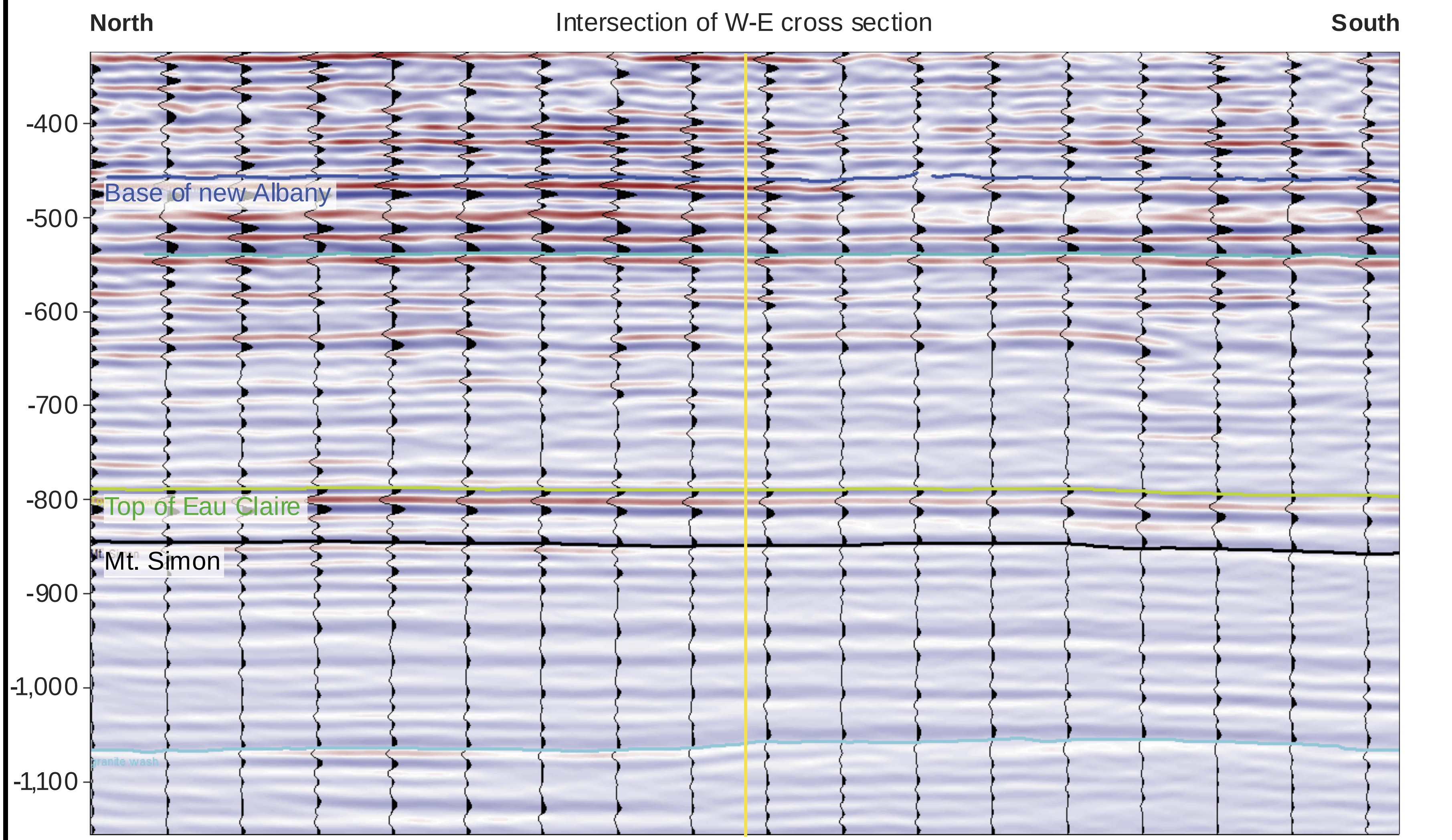


Figure 2-5: Location of cross-sections illustrating the regional geology of the injection site (Figure 2-6 and 2-7 are cross-sections referenced). Source: Smith, Schlumberger Carbon Services, 2011

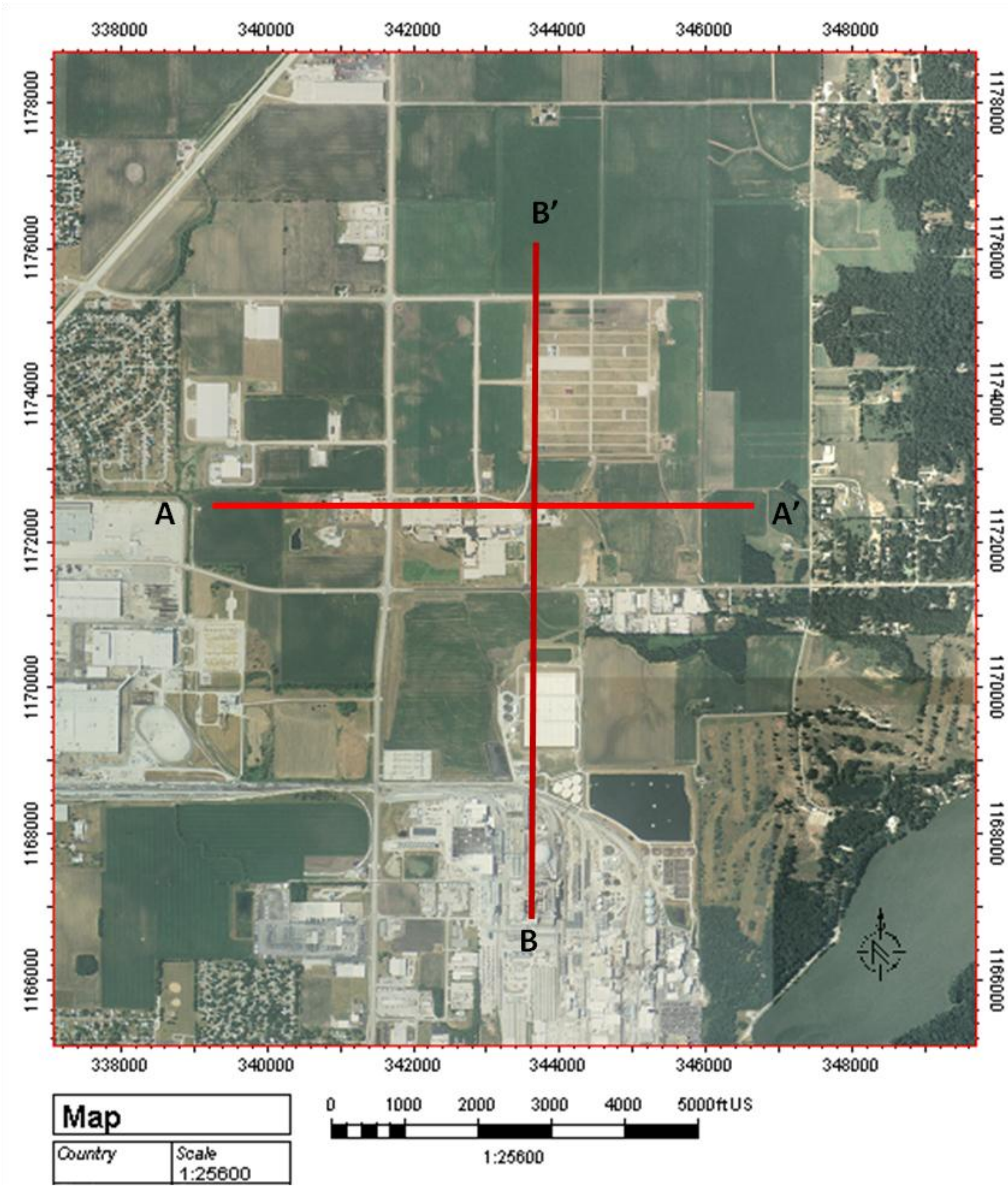


Figure 2-6: Cross section illustrating the geology along west (A) to east (A') direction (location given by Figure 2-5). Source: Smith, Schlumberger Carbon Services, 2011

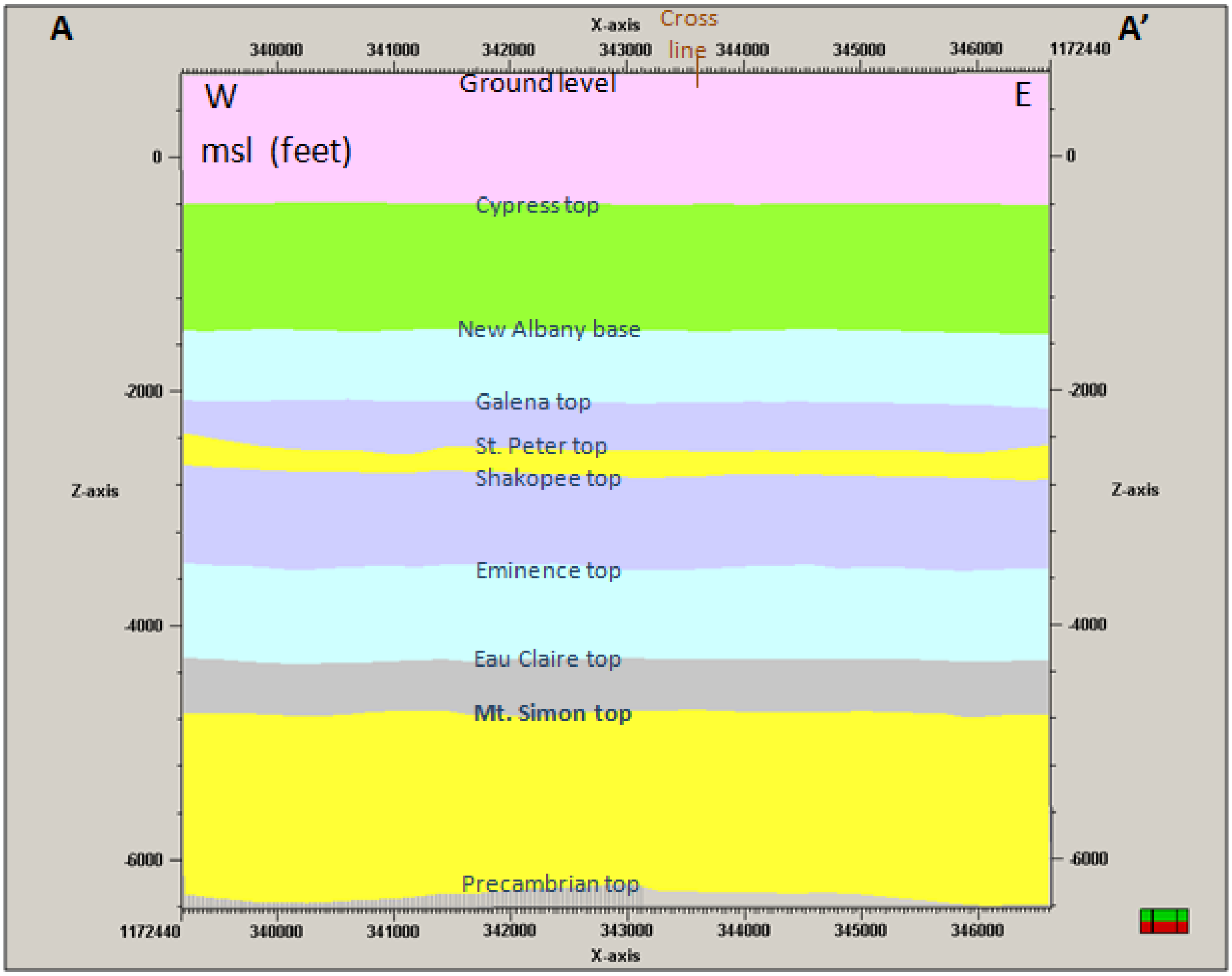


Figure 2-7: Cross section illustrating the geology along south (B) to north (B') direction (location given by Figure 2-5). Source: Smith, Schlumberger Carbon Services, 2011 .

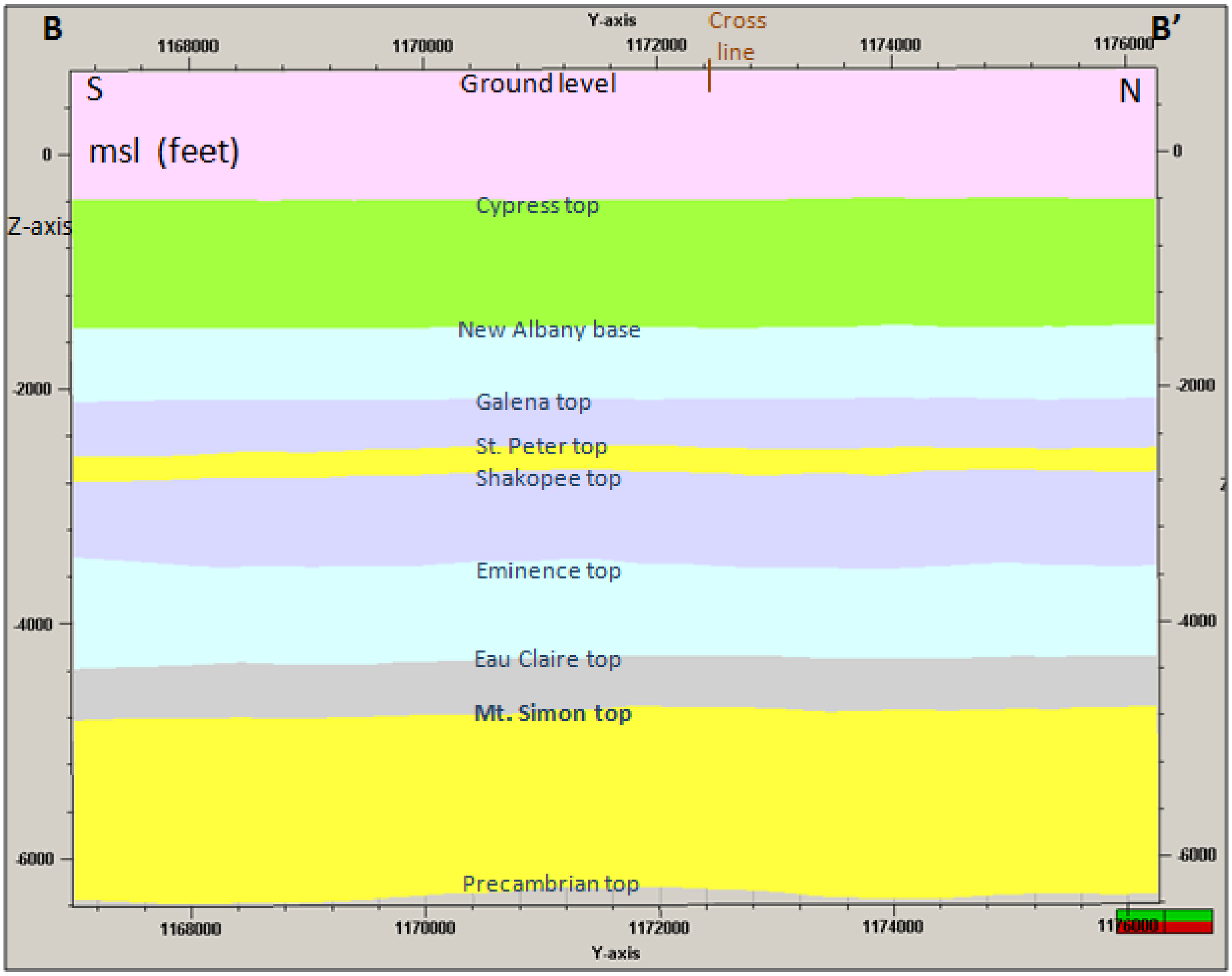


Figure 2-8: Stratigraphic column of Ordovician through Precambrian rocks in northern Illinois (Kolata, 2005). Arrows point to the formations discussed in this UIC permit application. Dr. Darriwillian; Dol, dolomite; Fm, formation; Ls, limestone; MAYS., Maysvillian; Mbr, Member; Sh, shale; WH., Whiterockian; Mya, million years ago; Ss, sandstone; Silts, siltstone.

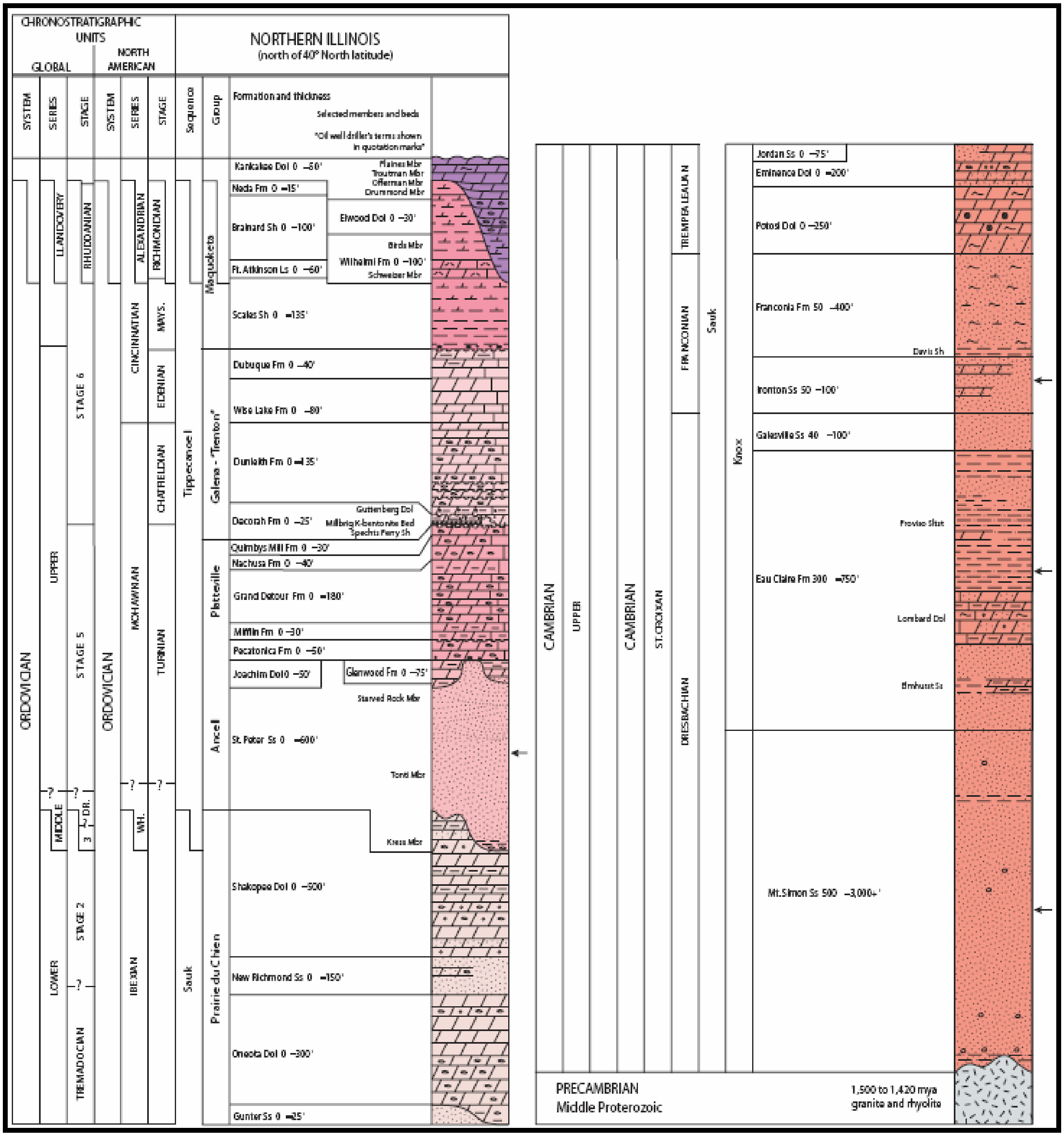


Figure 2-9: Stratigraphic cross section through the Weaber Horn #1, Harrison #1, CCS #1 and the Hinton #7 wells showing the Mt. Simon porosity. The red colored zones have porosity greater than 10% (Frommelt, 2010).

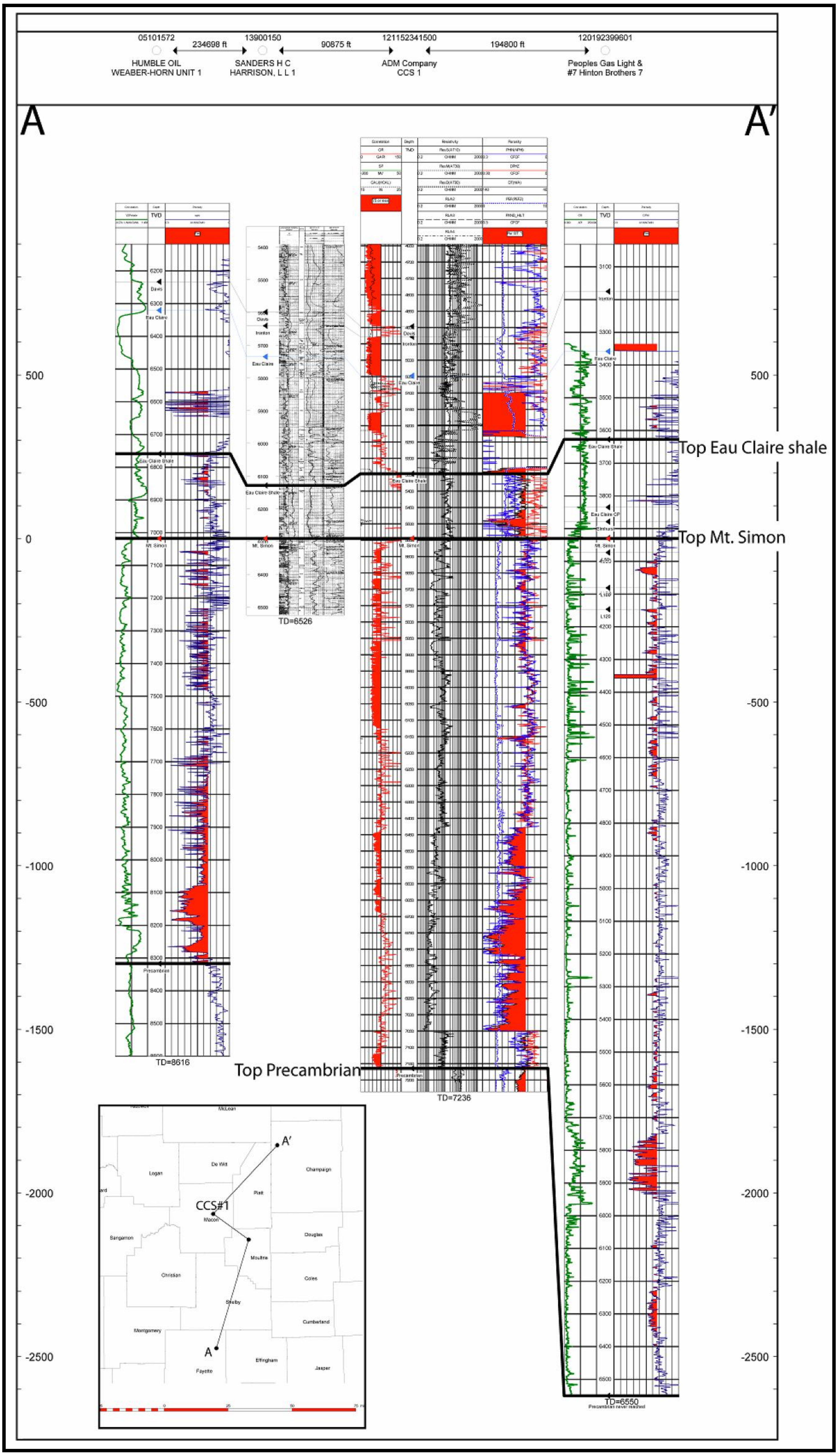


Figure 2-10: IBDP CCS #1 step-rate test with fracture propagation pressure of 4966 psig estimated from the intersection of the two lines. The first line (2-6 bpm) represents radial flow of the Mt. Simon; the second line 7-8 bpm represents flow into the Mt. Simon after a fracture has propagated. The perforated interval was 7,025 to 7,050 feet during this step-rate test. These results correspond to a fracture gradient of 0.715 psi/ft. Source: Frommelt, 2010.

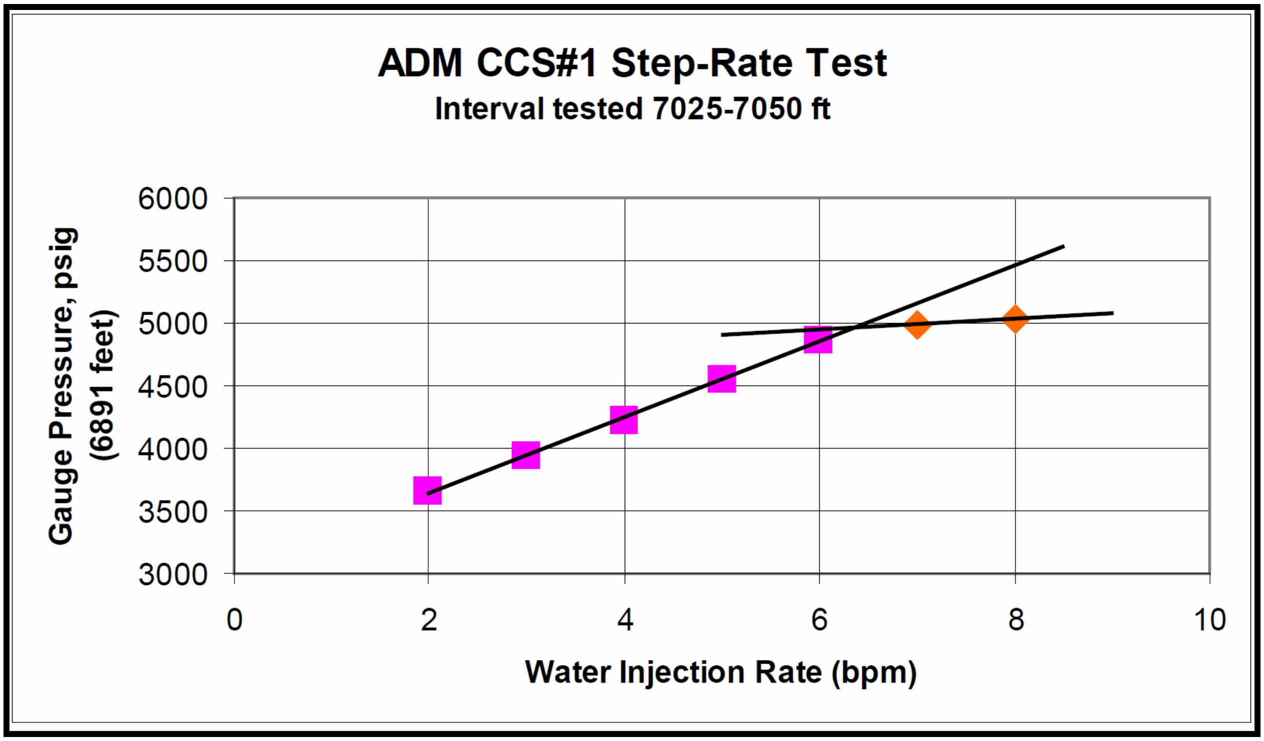


Figure 2-11: Crossplot of helium porosimeter and neutron-density data for CCS #1. The bold line through the data is the unit slope, showing very good correlation between the two types of porosity data. For the porosity data from the rotary sidewall core plugs and the neutron-density crossplot porosity at the interval of the core plug, the porosity compares relatively well such that total and effective porosity are very similar. Source: Frommelt, 2010.

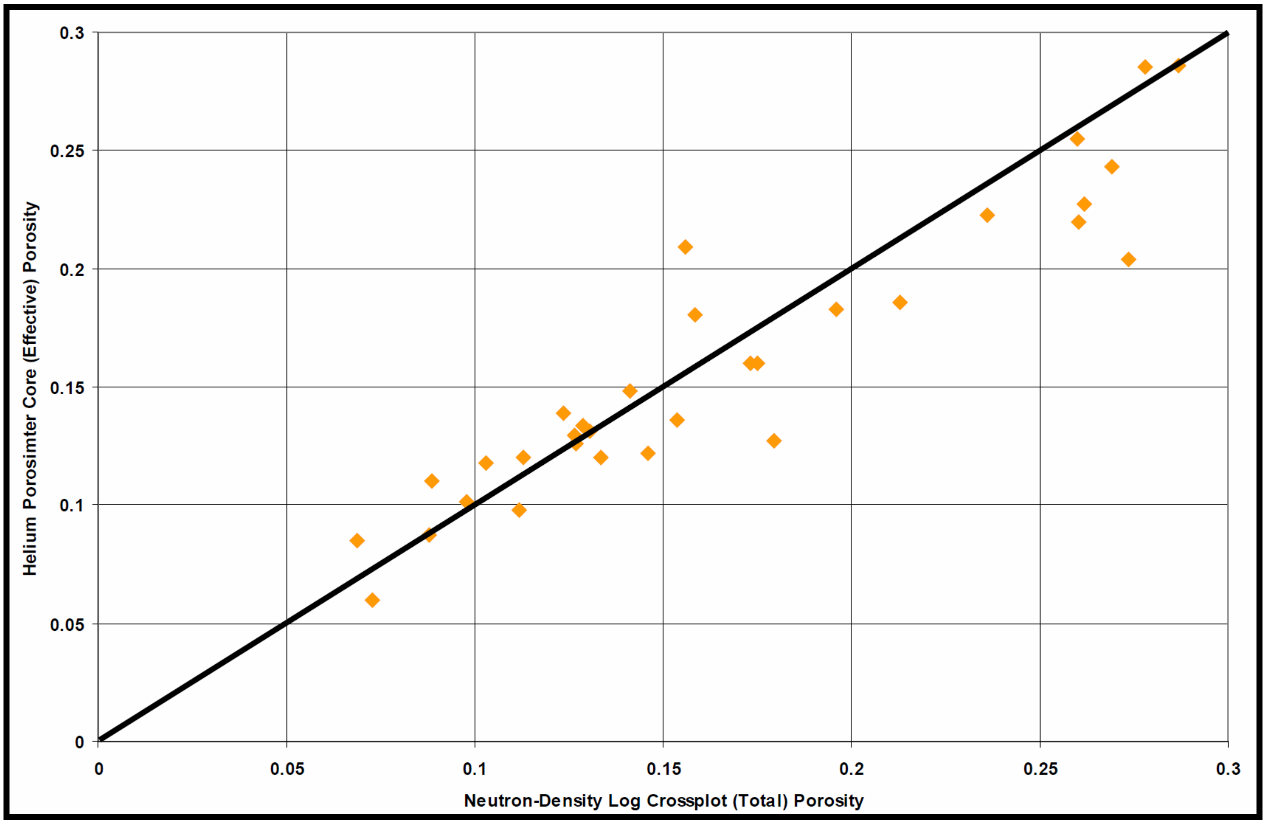


Figure 2-12. Crossplot of core permeability versus core porosity for CCS #1. Transforms were developed for three different grain sizes—fine grained, medium grained and coarse grained sandstone. Source: Frommelt, 2010.

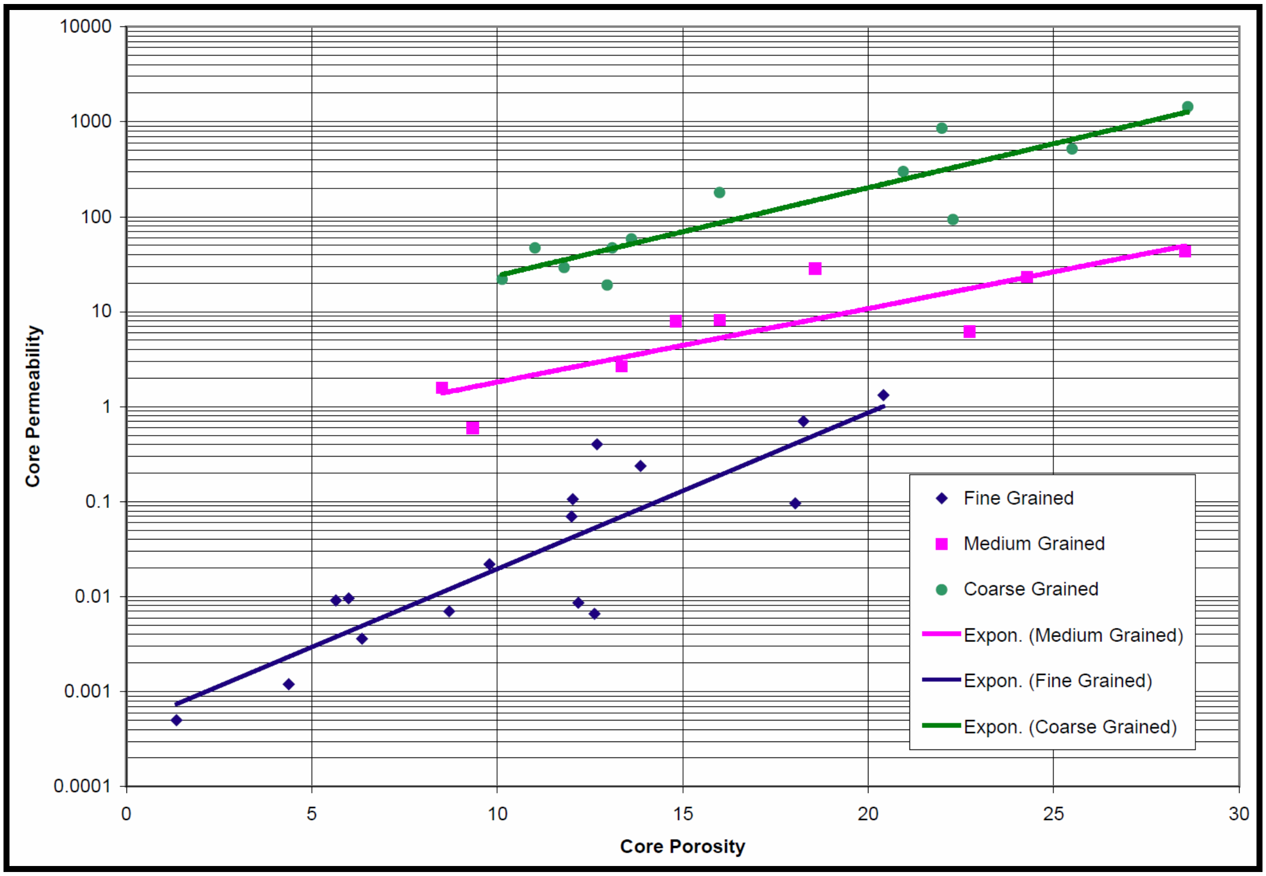


Figure 2-13: Qualitative derivative analyses of final pressure falloff test conducted in CCS #1. Radial pressure response is indicated by a horizontal derivative trend. Two periods were measured during this test between 0.1 and 1 hours (PPNSTB) and 20 to 100 hours (STABIL). The first period corresponds to radial flow across the perforated interval; the second period corresponds to the larger thickness that would be between two much lower permeability sub-units e.g, the less permeable arkose-rich interval at the base and a tighter interval above the perforated interval. The transition between the two radial responses (SPHERE) is a spherical flow period that is influenced by vertical permeability (or kv/kh). (The unit slope (UNIT SLP) indicating wellbore storage, identifies the end of wellbore storage influenced pressure data (ENDWBS) or pressure data that can be analyzed from reservoir properties.). Source: Frommelt, 2010.

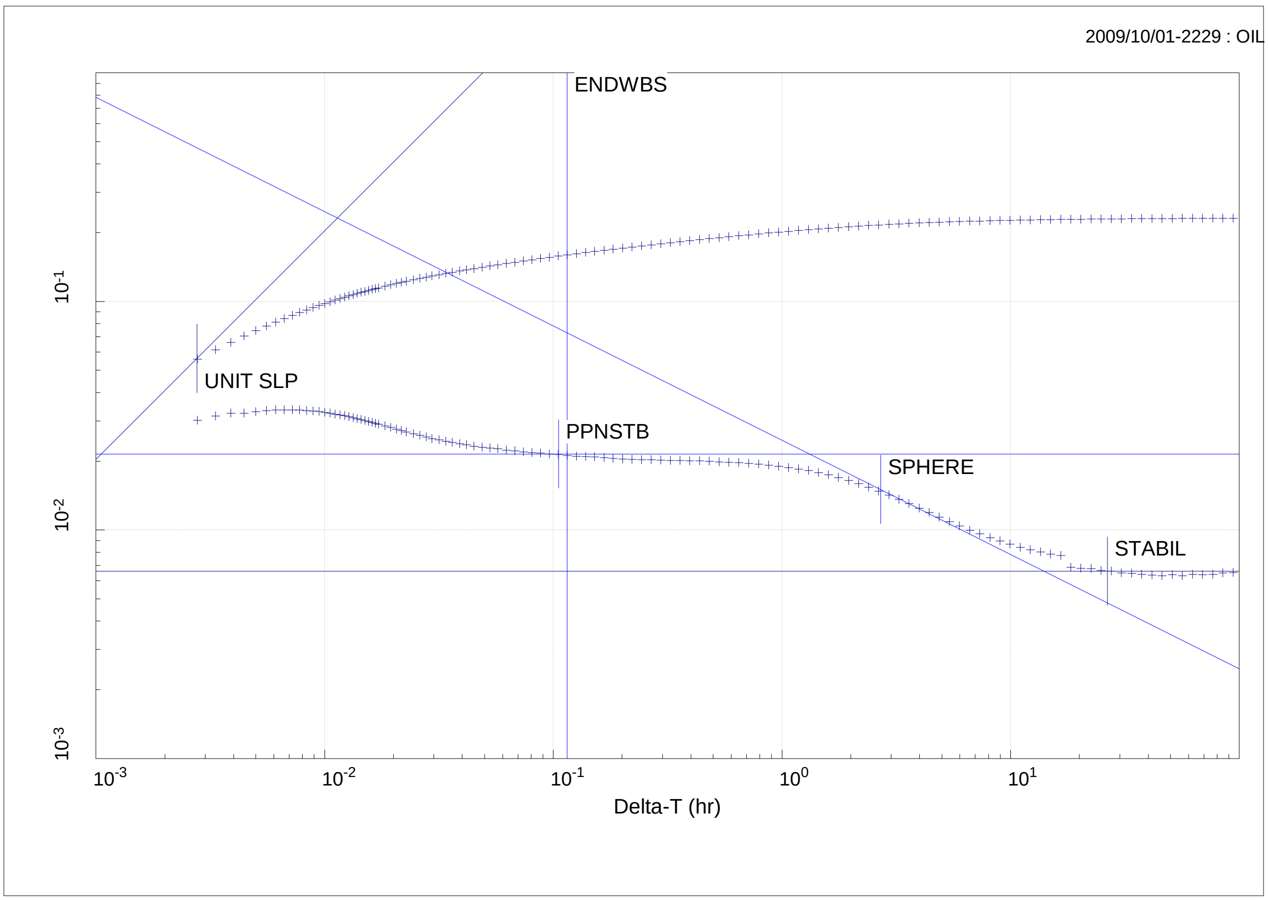


Figure 2-14: Overlay of pressure derivative of the three pressure falloff tests conducted in CCS #1. The Green curve (upper pressure curve and bell shaped derivative) is the first falloff which had perforated interval of 7025-7050 ft MD. The pink (lower derivative curve) is the second falloff in the same perforated interval which had a modest acid treatment prior to the falloff. The dark blue (lower pressure curve middle derivative curve) was the third falloff tests for the perforated intervals of 6982-7012 and 7025-7050 ft MD and a second acid treatment over both perforated intervals. The difference between the green curve and the pink curve in the first 6 minutes is a result of the improvement to flow due to the acid treatment. The upper curves show the pressure difference and the lower curves show the derivative. Source: Frommelt, 2010.

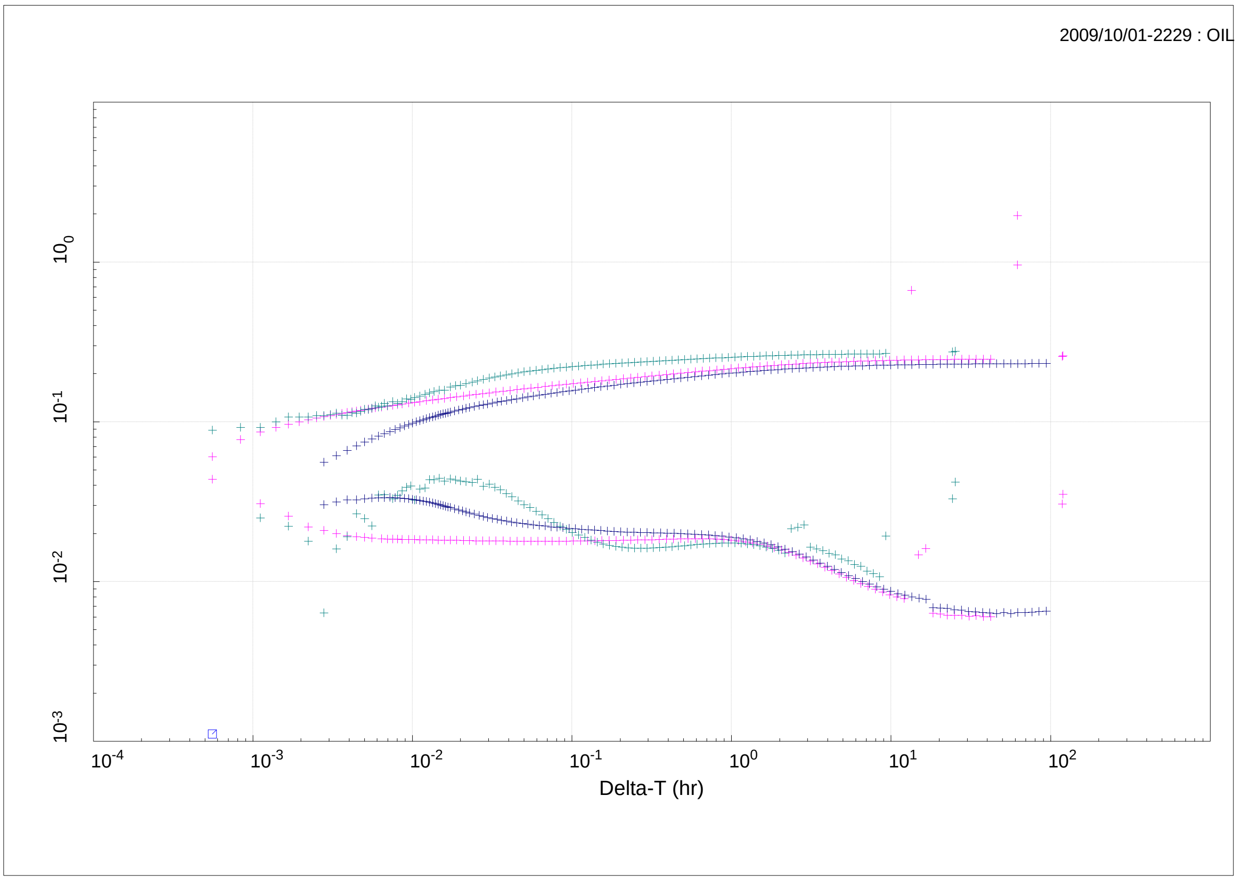
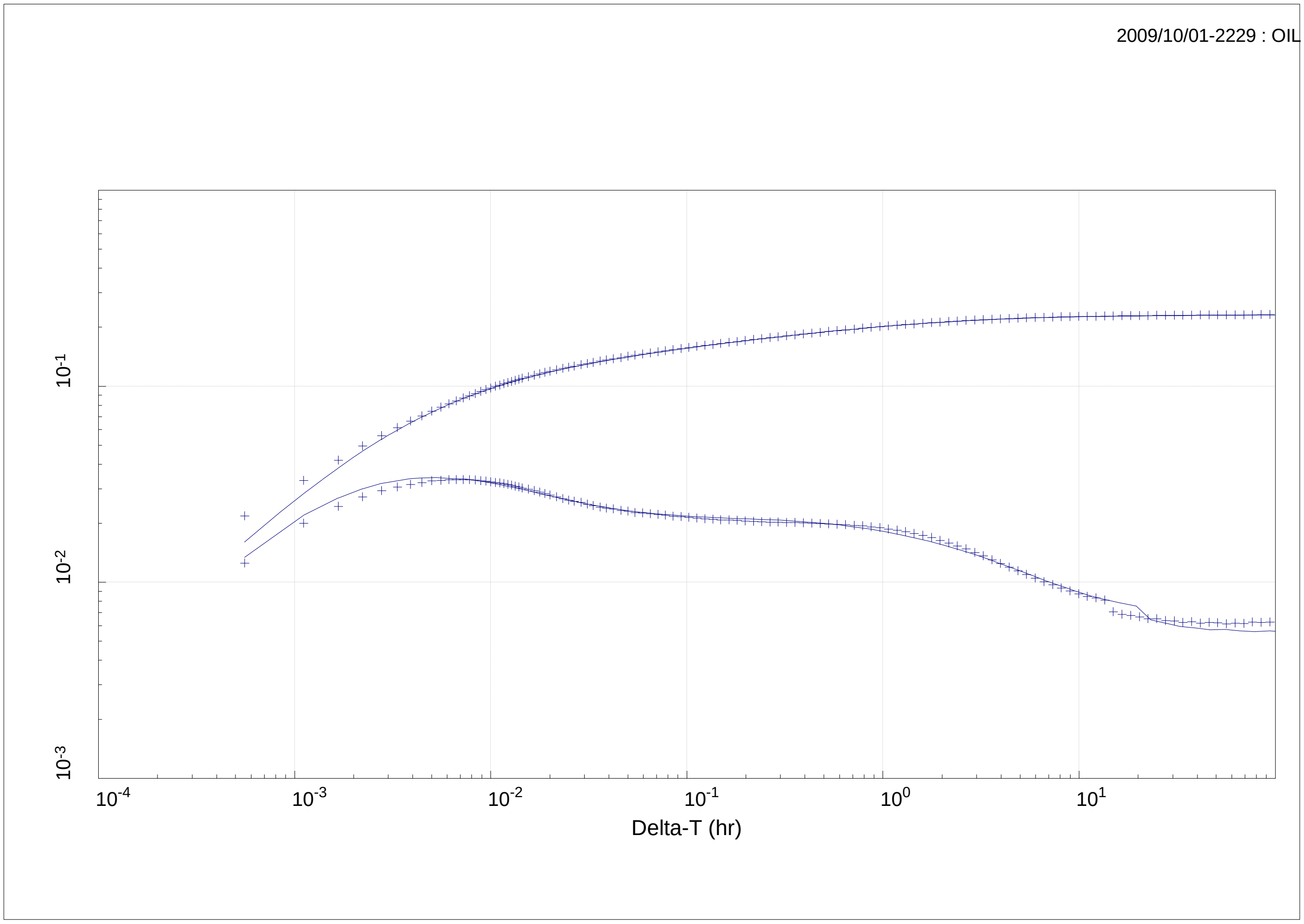


Figure 2-15: Nonlinear regression, or simulation history matching, of the of final pressure falloff test conducted in CCS #1. Test data shown as + symbols and simulated data shown as line. The upper curve is the pressure difference and the lower curve is the derivative. Source: Frommelt, 2010.




```
Partial Penetration Well
** Simulation Data **                      Type-Curve Model Static-Data
 well. storage   = 0.0011457 BBLS/PSI      Perf. Interval = 25.0 FEET
 Skin(mech.)     =  -0.85807
 permeability    =    184.58 MD            Static-Data and Constants
 Kv/Kh           =  0.013260               Volume-Factor  = 1.000 vol/vol
 Eff. Thickness =    75.000 FEET           Thickness      = 75.00 FEET
 Zp/Heff         =   0.83330               Viscosity      = 1.300 CP
 Skin(Global)    =    10.301               Total Compress = .1800E-04 1/PSI
 Perm-Thickness =    13843. MD-FEET        Rate           = -6100. STB/D
```

Figure 2-16: Observed head in the Mt. Simon sandstone. Groundwater flows from areas of higher head to lower head, along lines perpendicular to the head lines. Contour interval = 25 m. (modified from Gupta and Bair, 1997). At the CCS #1 well (red dot), the potentiometric surface was calculated to be 76 m above mean sea level.

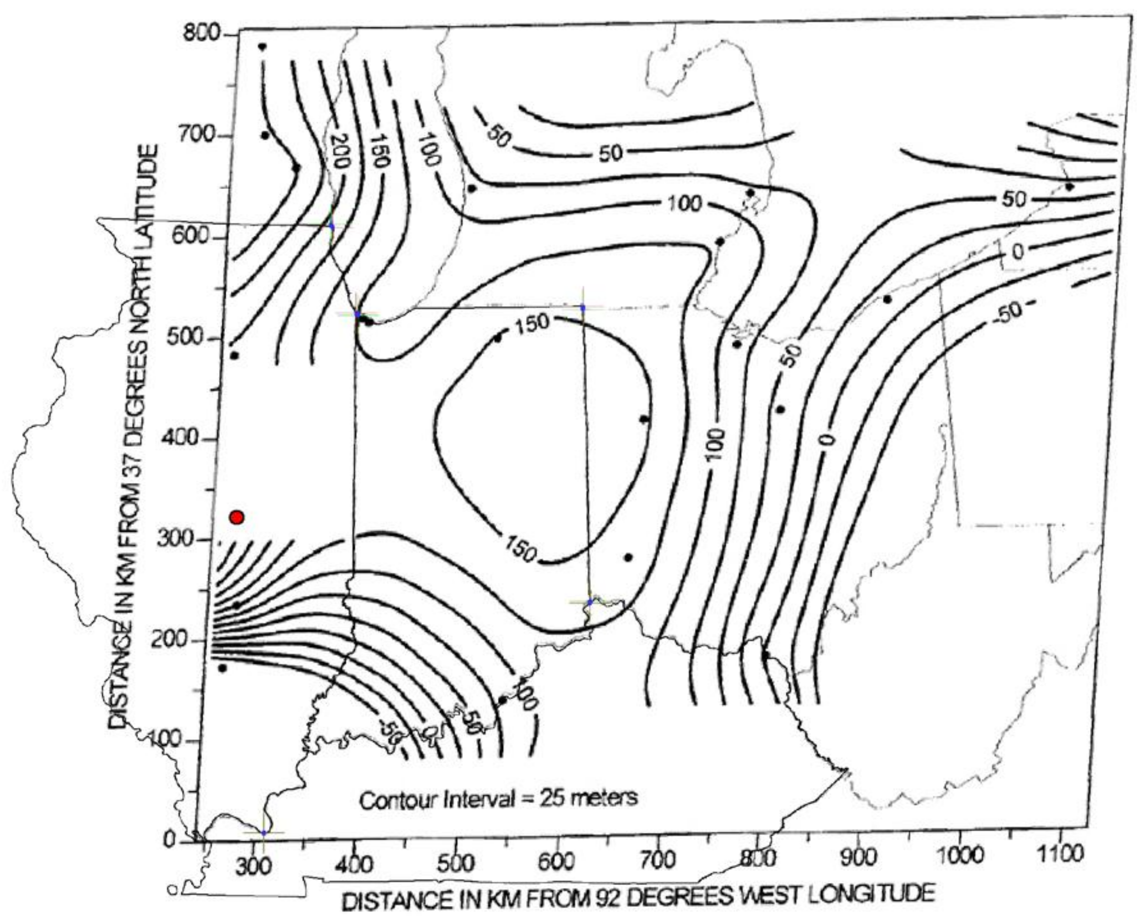


Figure 2-17: Observed vertical flow components in the Mt. Simon Sandstone around the Upper Midwest with the Michigan Basin based on Vugrinovich (1986), (from Gupta and Bair, 1997).

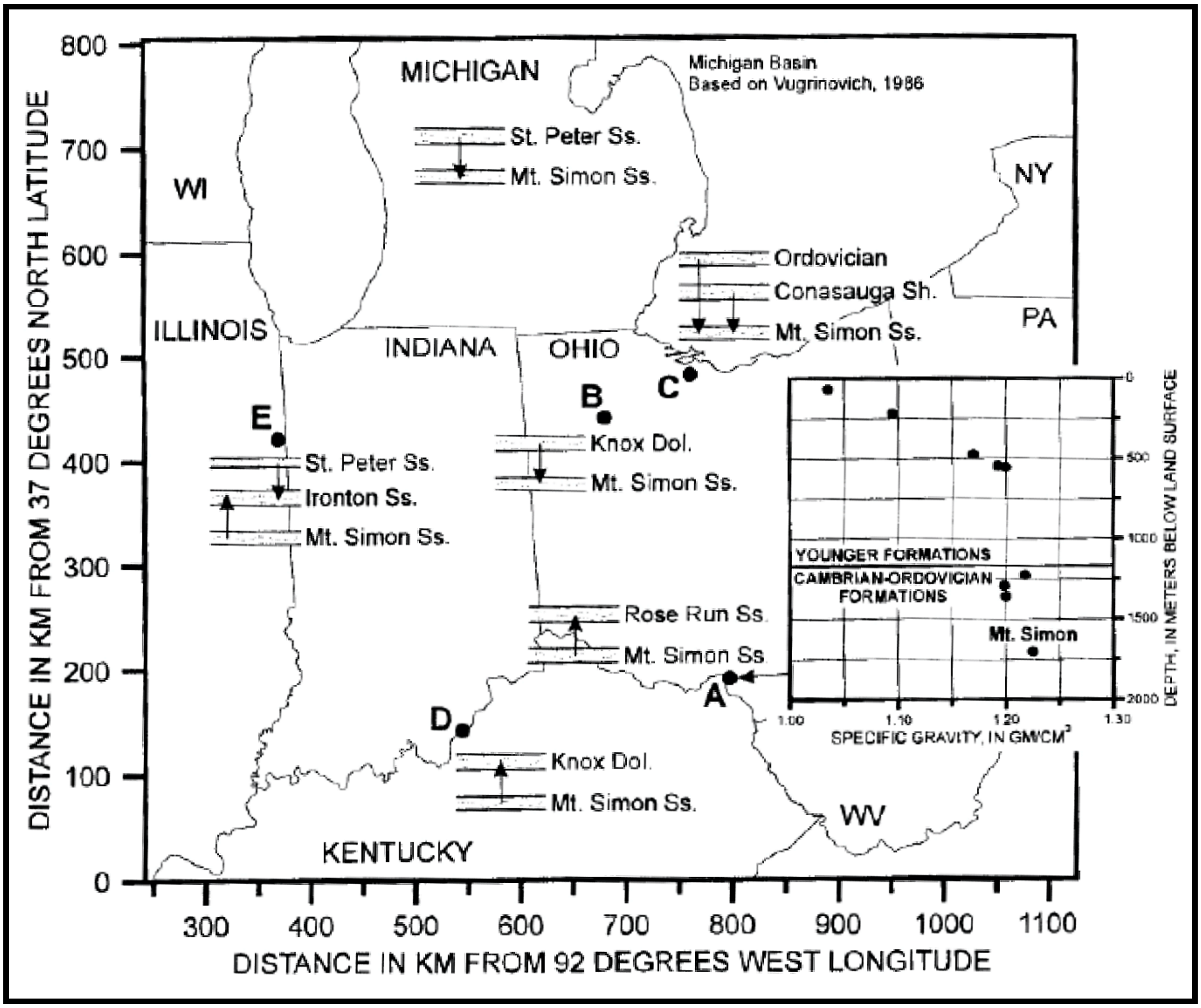


Figure 2-18: Relation between relative density and dissolved solids content of brines in deep aquifers of the Illinois Basin. Source: Bond (1972).

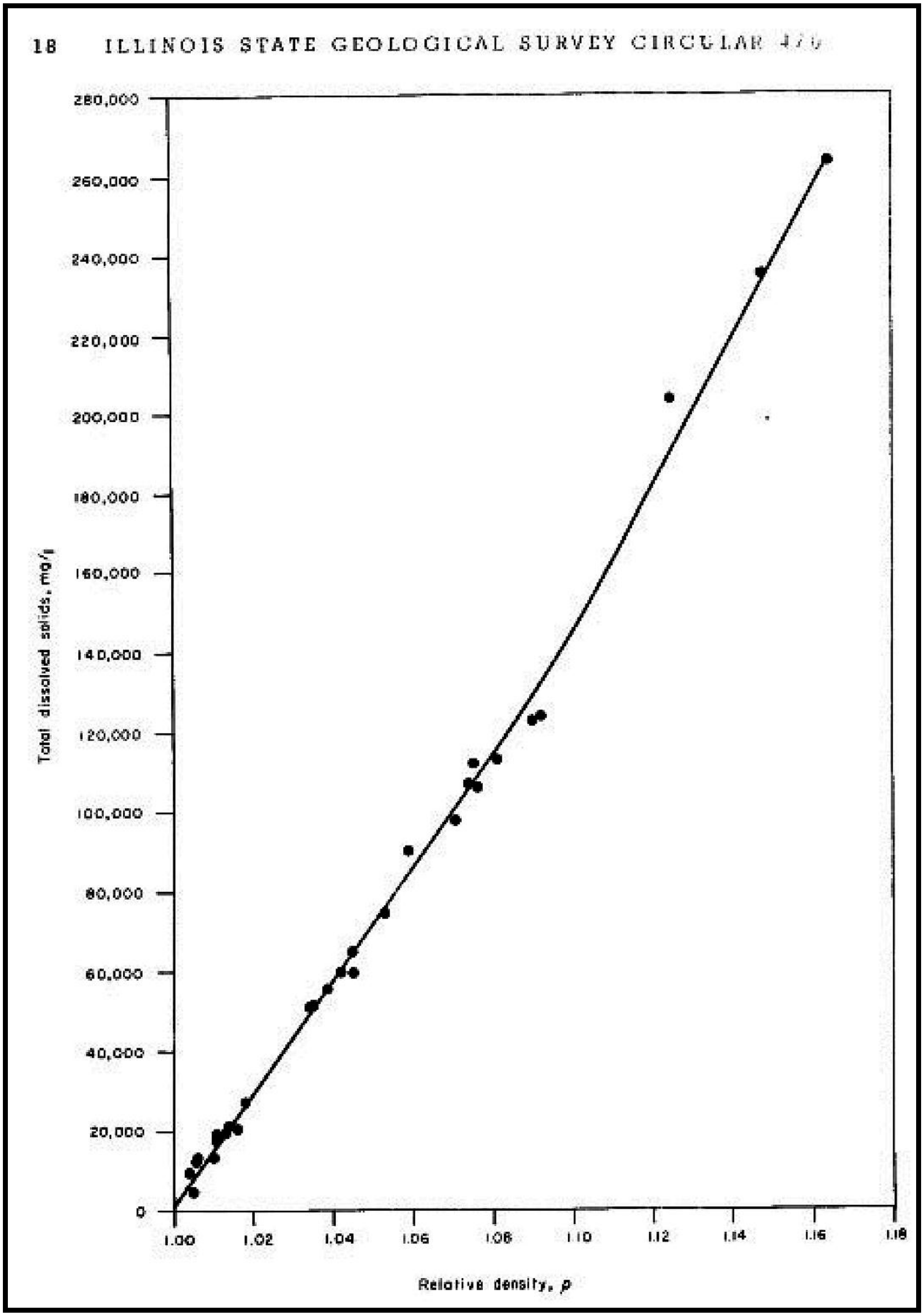


Figure 2-19: Total dissolved solids (TDS) within the formation water of the Mt. Simon Reservoir

Source: Modified from Finley, 2005.

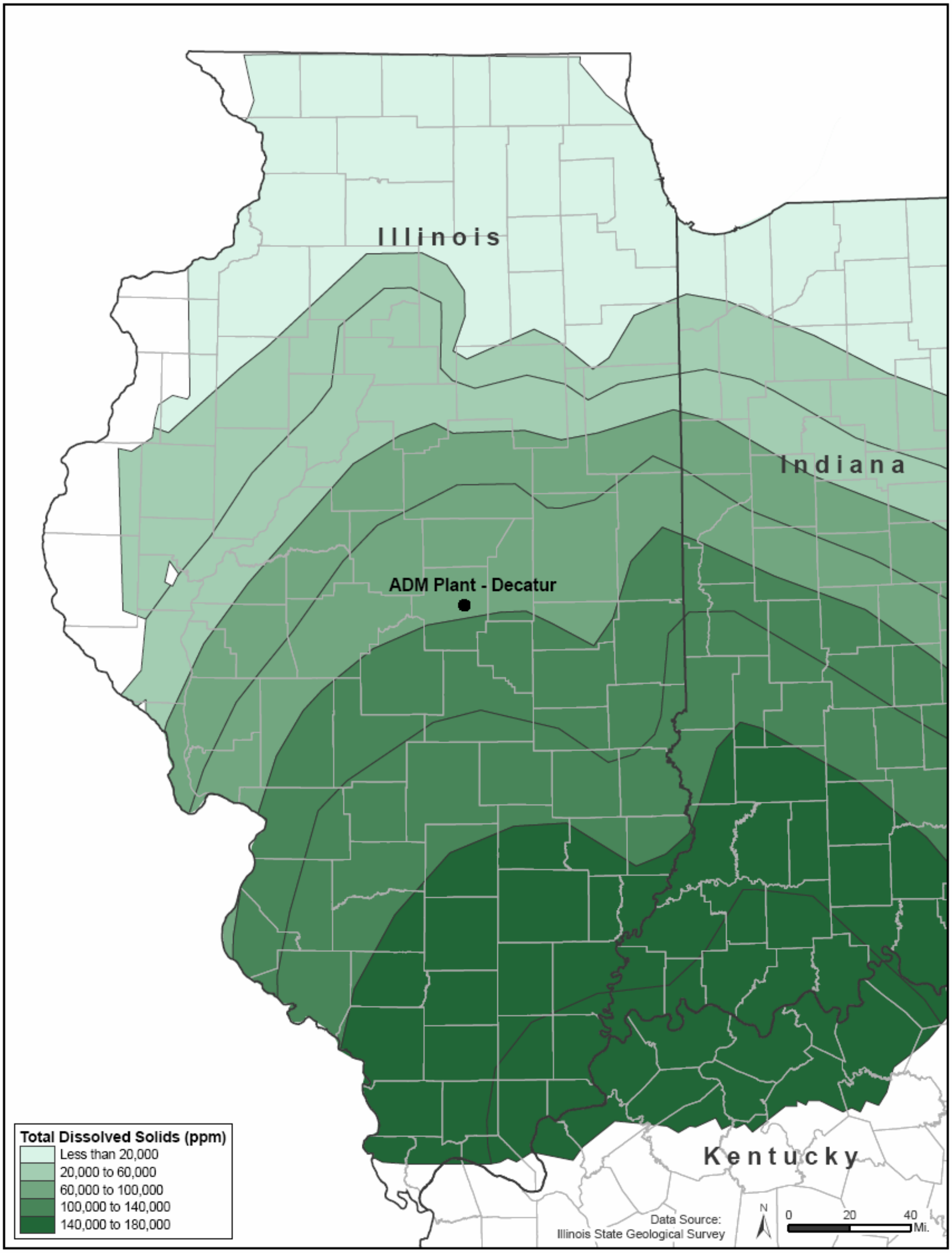


Figure 2-20: Diagrammatic cross section of the Cambrian System from northwestern to southeastern Illinois. The orange color shows the areas where the Eau Claire Formation is primarily shale and should be a good seal. Uncolored areas may behave as seals, but there is an enhanced risk for leakage because of fracturing (modified after Willman et. al., 1975).

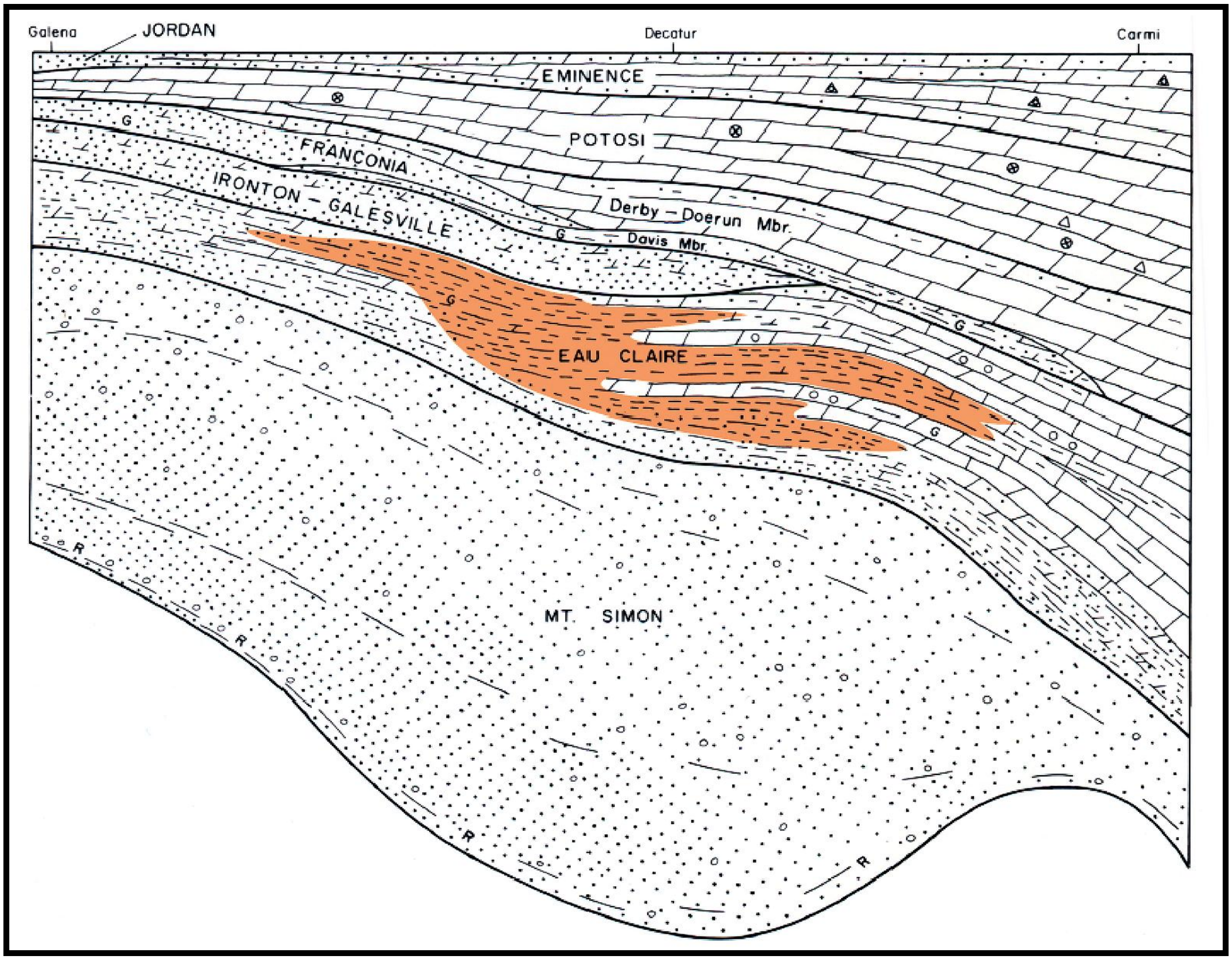


Figure 2-21: Thickness (feet) of the New Albany Shale.
Proposed injection well is near the center of Section 32 (shaded purple). Source: Leetaru, 2007.

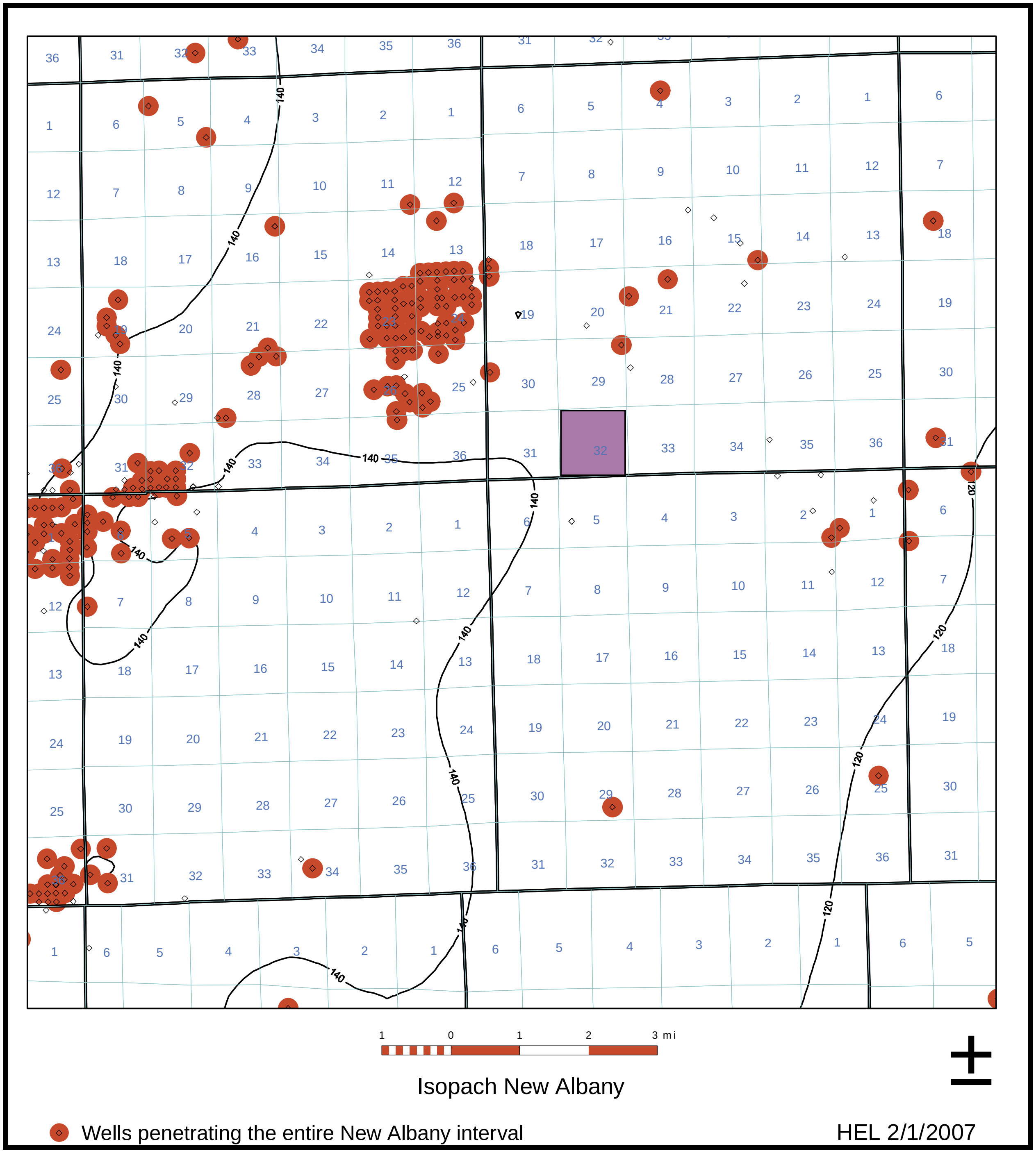


Figure 2-22: Isopach of the Ironton-Galesville Sandstone in Illinois. The orange line signifies the southern limit of the formation. There are no sandstone facies south of this line. (Willman, et al, 1975). The approximate site location is denoted by the red square.

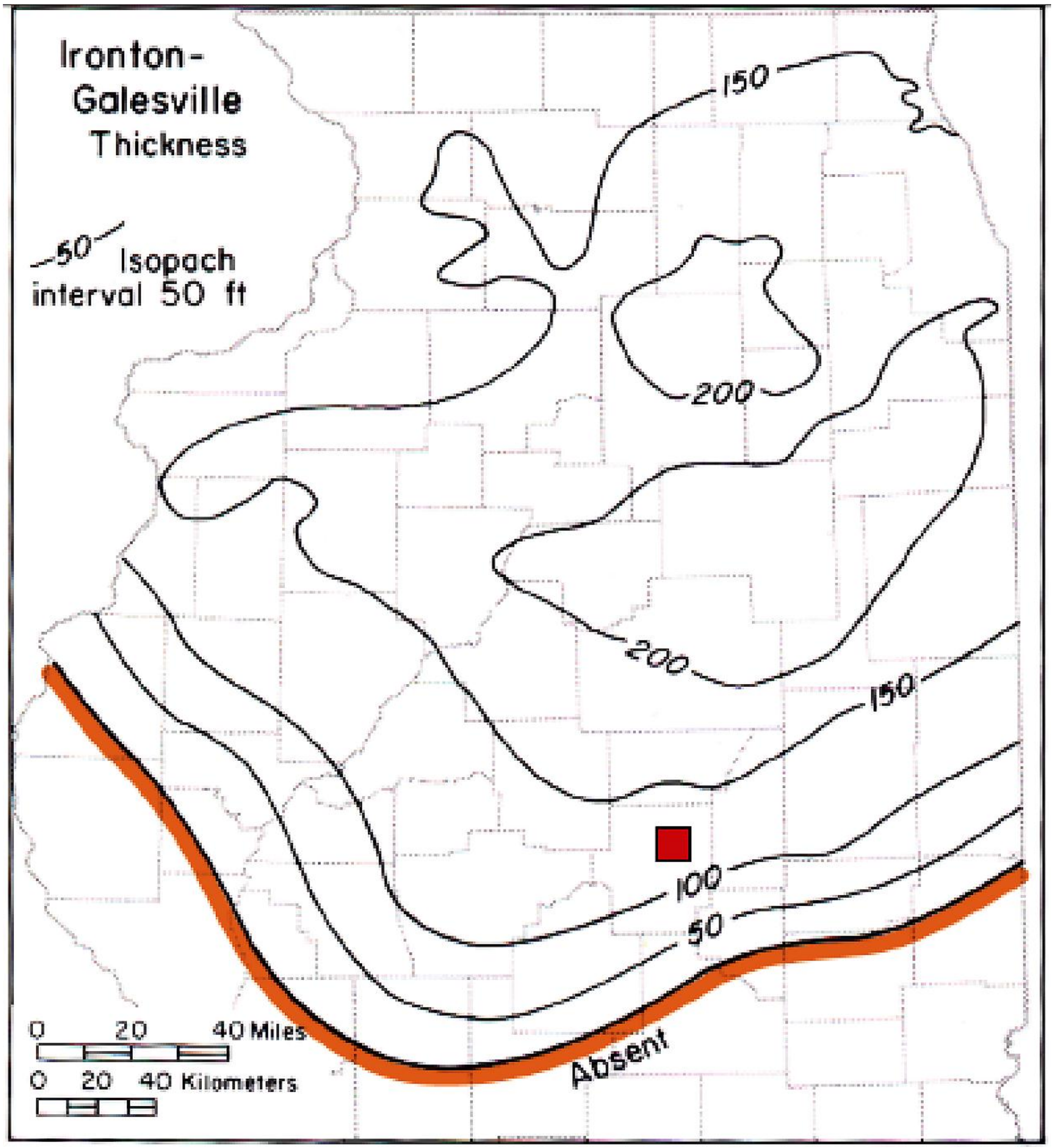


Figure 2-23: Regional map showing limits of fresh water in the Ironton-Galesville Sandstone. Proposed injection site should not encounter freshwater when drilling this formation. Source: Loyd, O,B. and W.L. Lyke, 1995, Ground Water Atlas of the United States, Segment 10: United States Geological Survey, 30 p. The red square denotes the relative location of the proposed injection site.

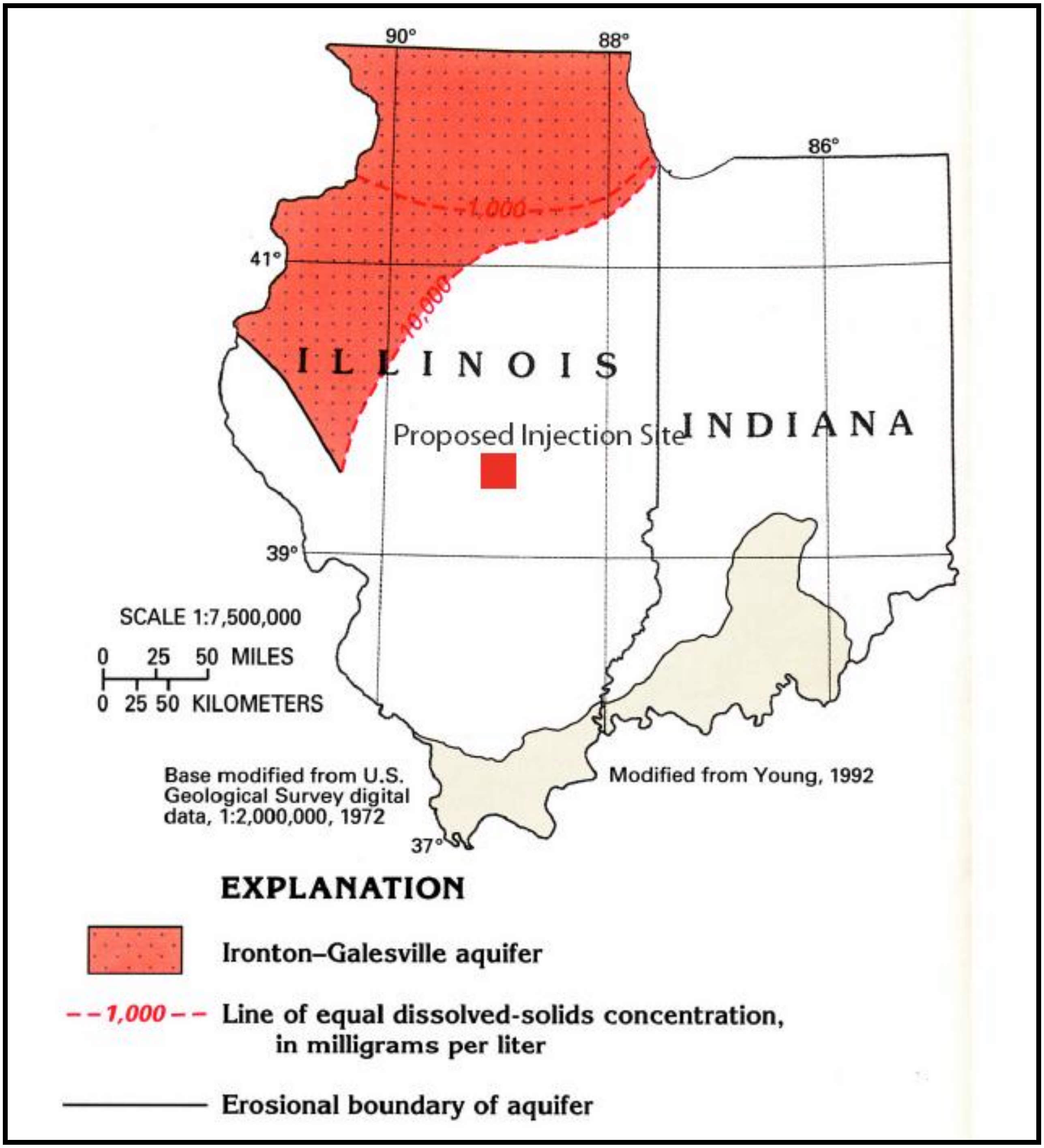


Figure 2-24: Regional Quaternary deposits near proposed IL-ICCS Injection Site, Decatur, IL. Source: ISGS Quarternary Deposits GIS Dataset, 1996.
http://www.isgs.illinois.edu/nsdihome/webdocs/st-geolq.html

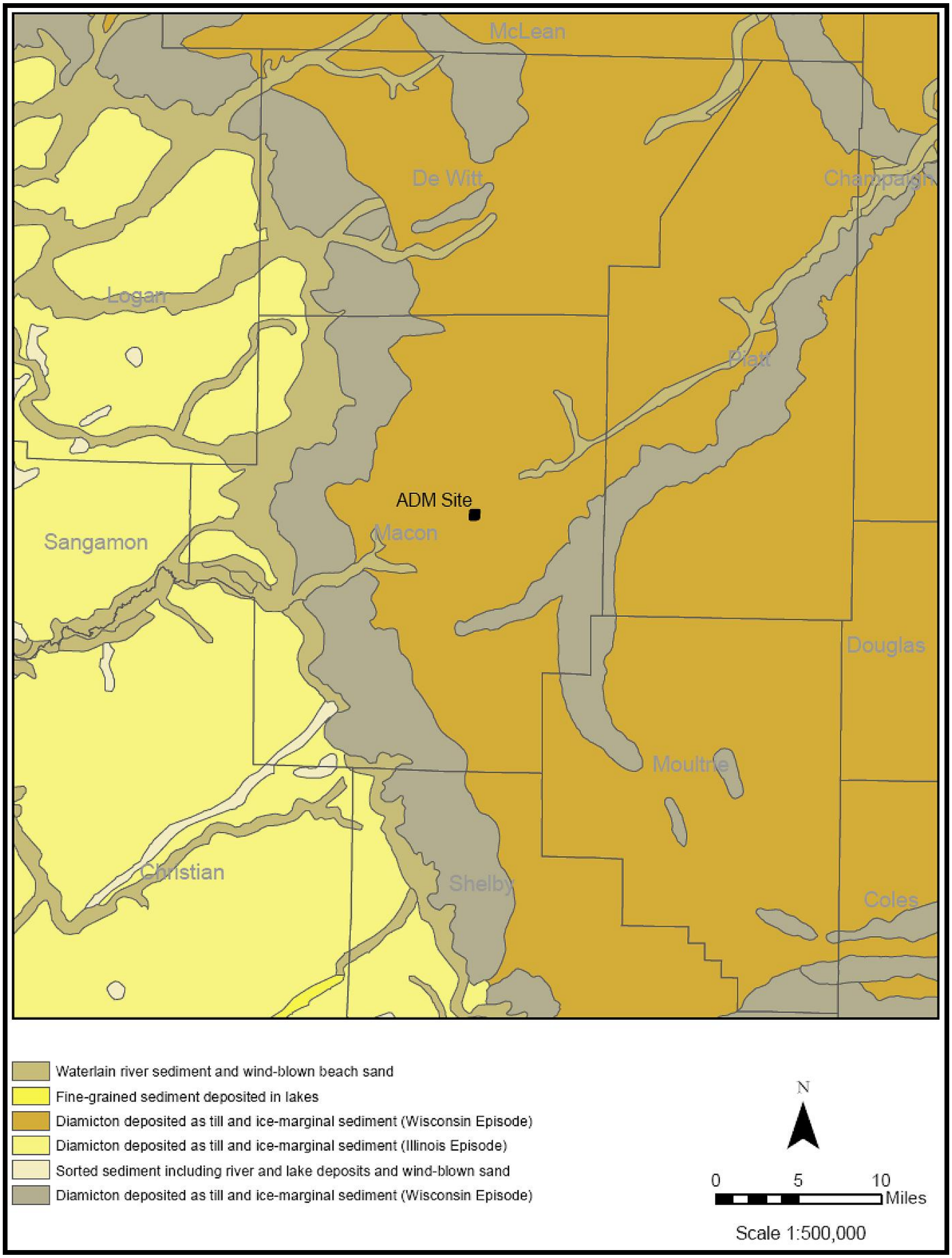


Figure 2-25: Schematic cross-section of aquifers within the Quaternary strata in the IL-ICCS area.

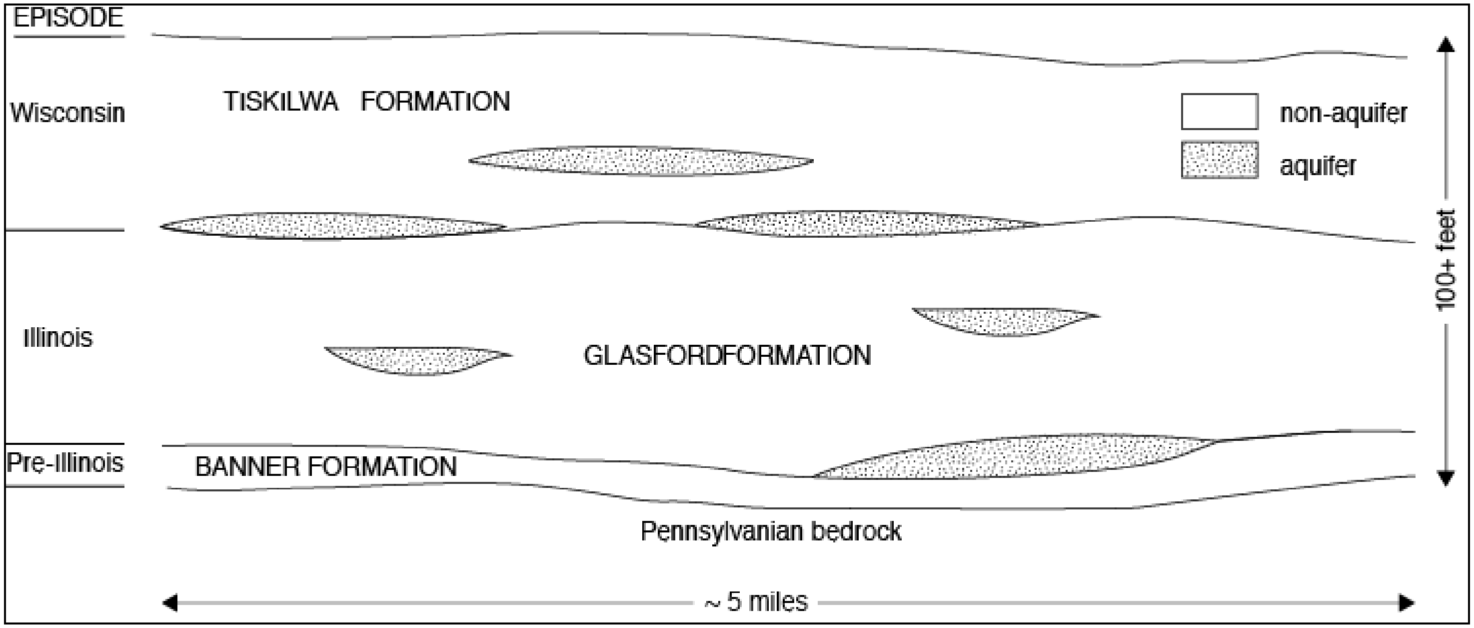


Figure 2-26: Depth to the top of the Mahomet aquifer (proposed injection well location in red) (Larson et al., 2003)

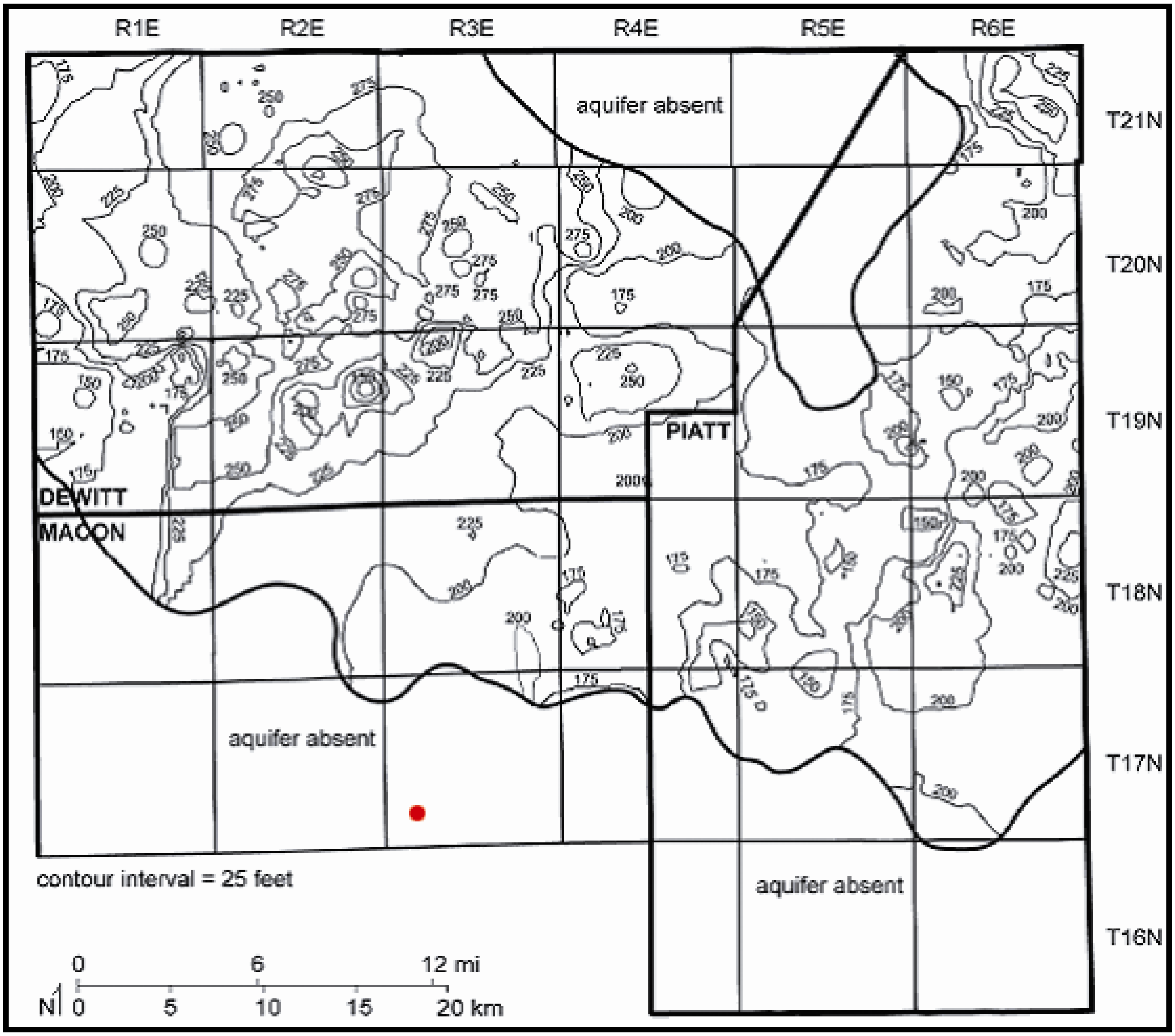


Figure 2-27: Thickness of the upper Banner aquifer (proposed injection well location in red) (Larson et al., 2003)

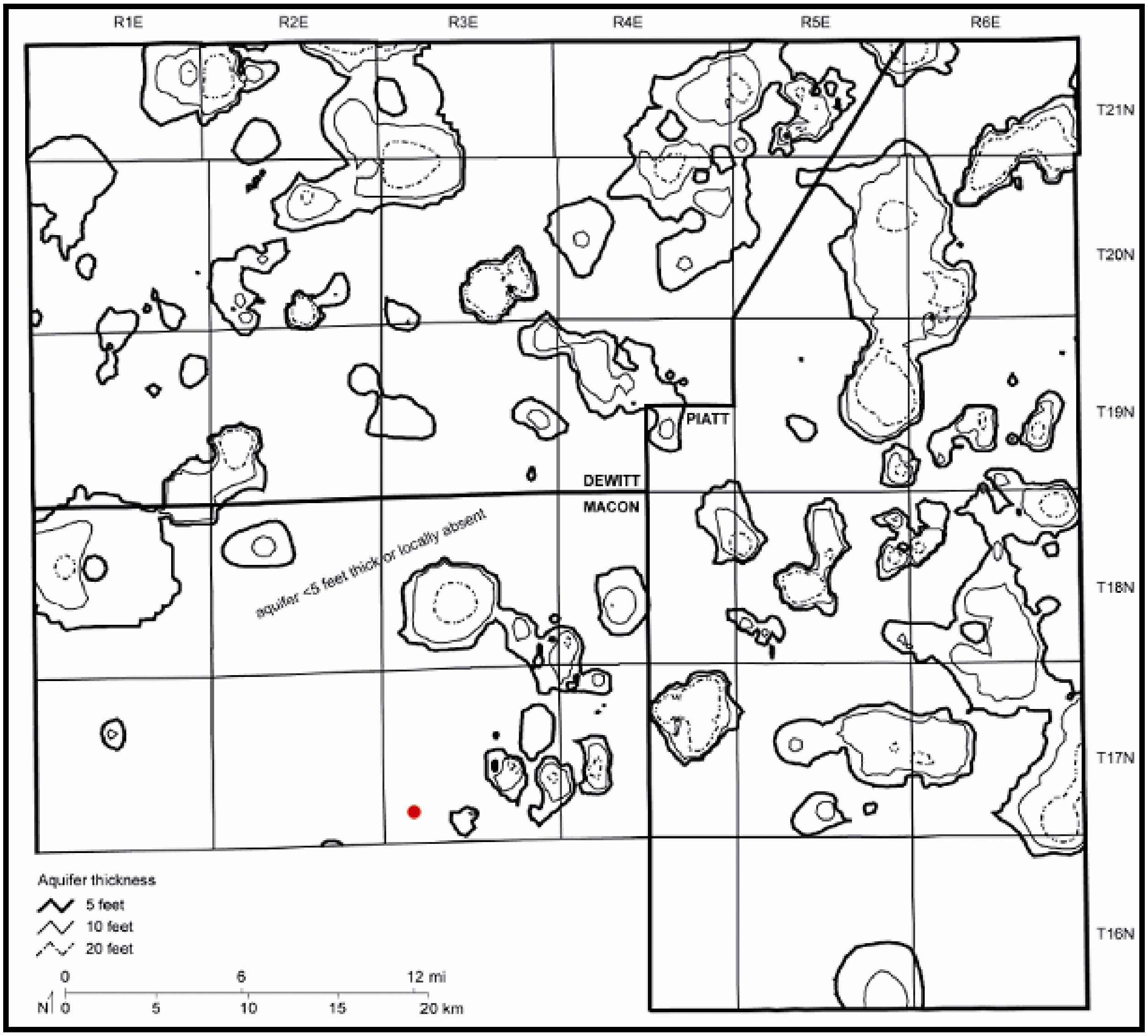


Figure 2-28: Thickness of the lower Glasford aquifer (proposed injection well location in red) (Larson et al., 2003)

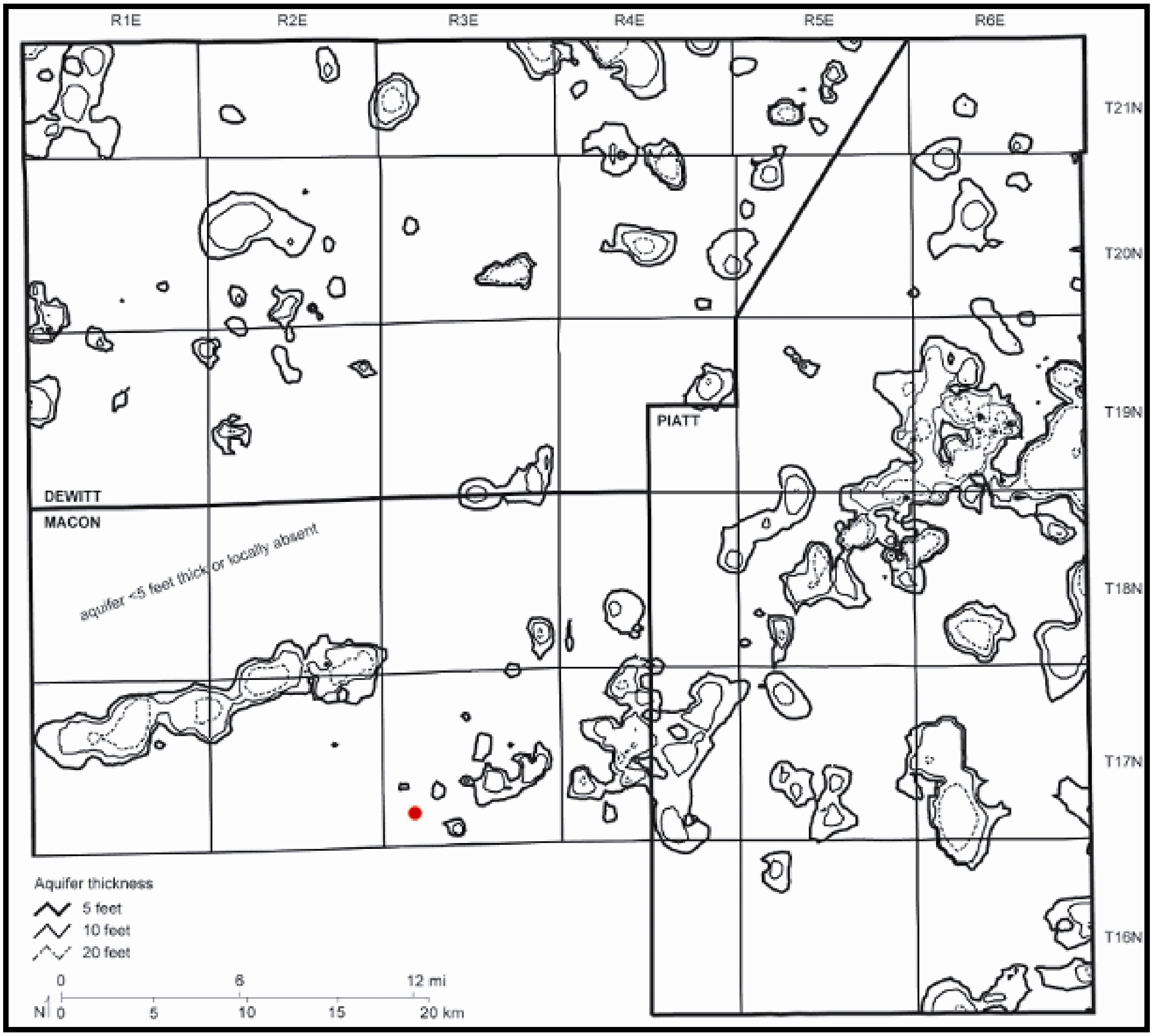


Figure 2-29: Thickness of the shallow sand aquifer (proposed injection well location in red) (Larson et al., 2003)

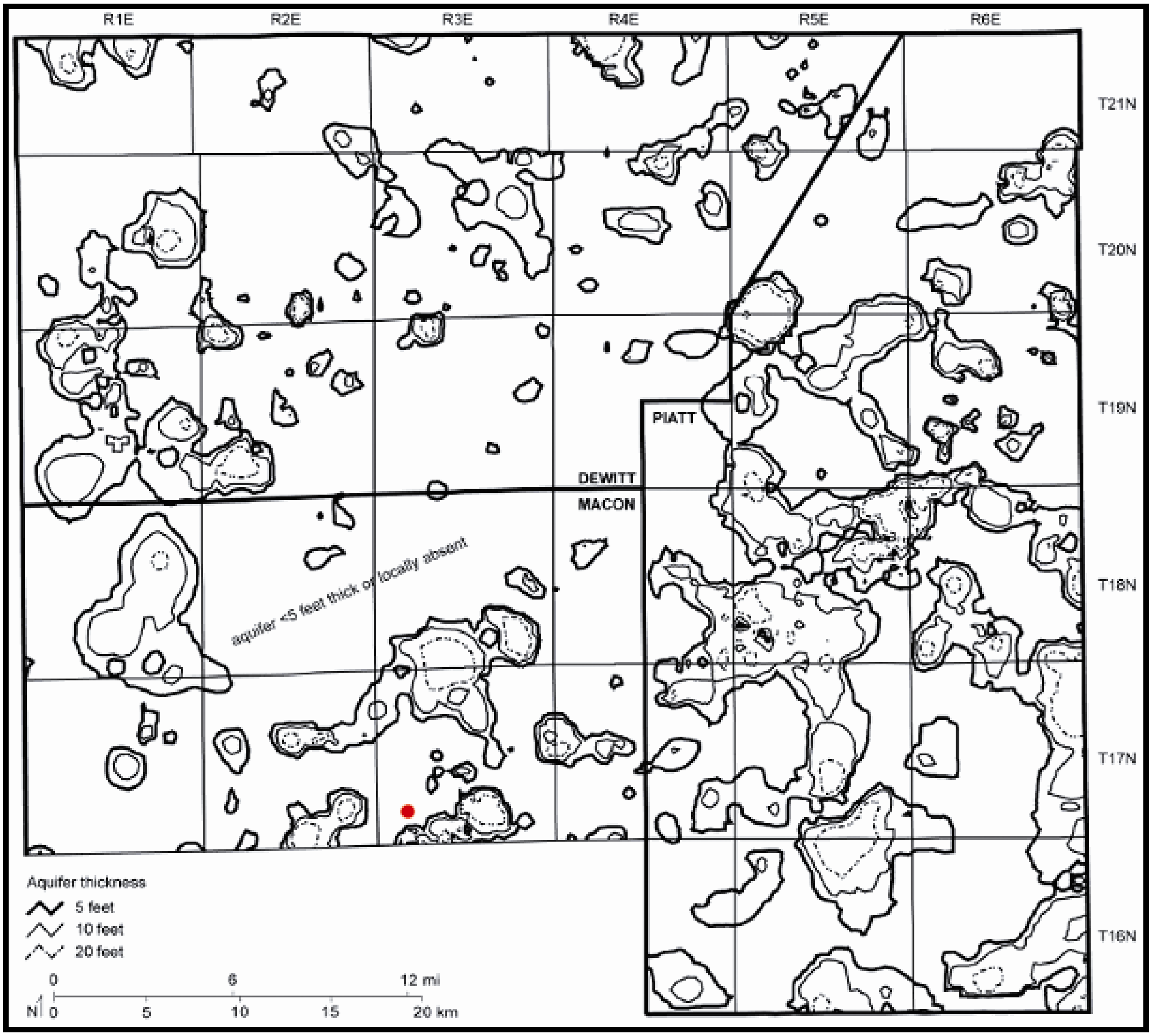


Figure 2-30: Thickness of the upper Glasford aquifer (proposed injection well location in red). (Larson et al., 2003)

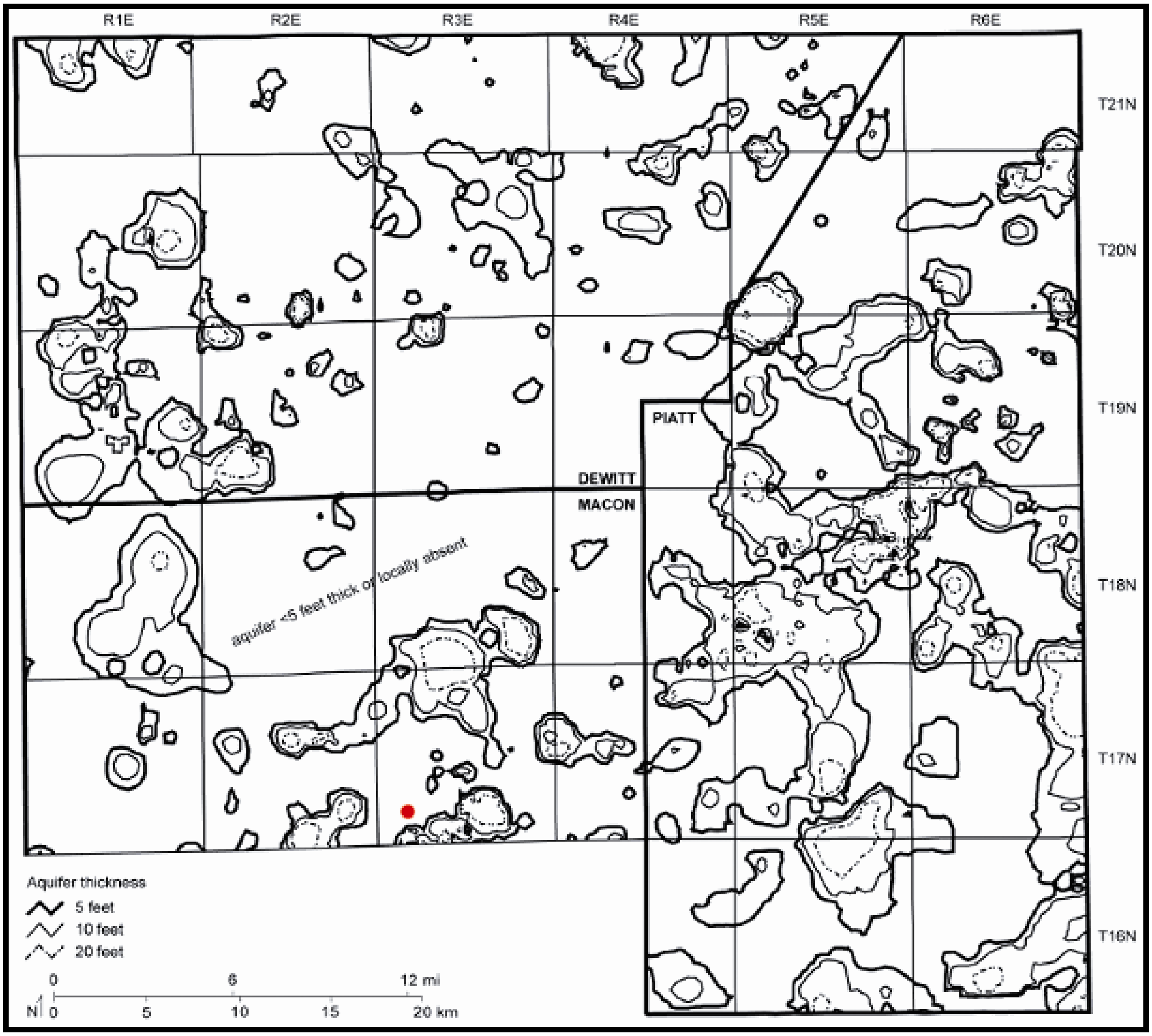


Figure 2-31: Regional bedrock geology near proposed IL-ICCS Injection Site, Decatur, IL. Source: ISGS Bedrock Geology GIS Dataset, 2005, http://www.isgs.illinois.edu/nsdihome/webdocs/st-geolb.html

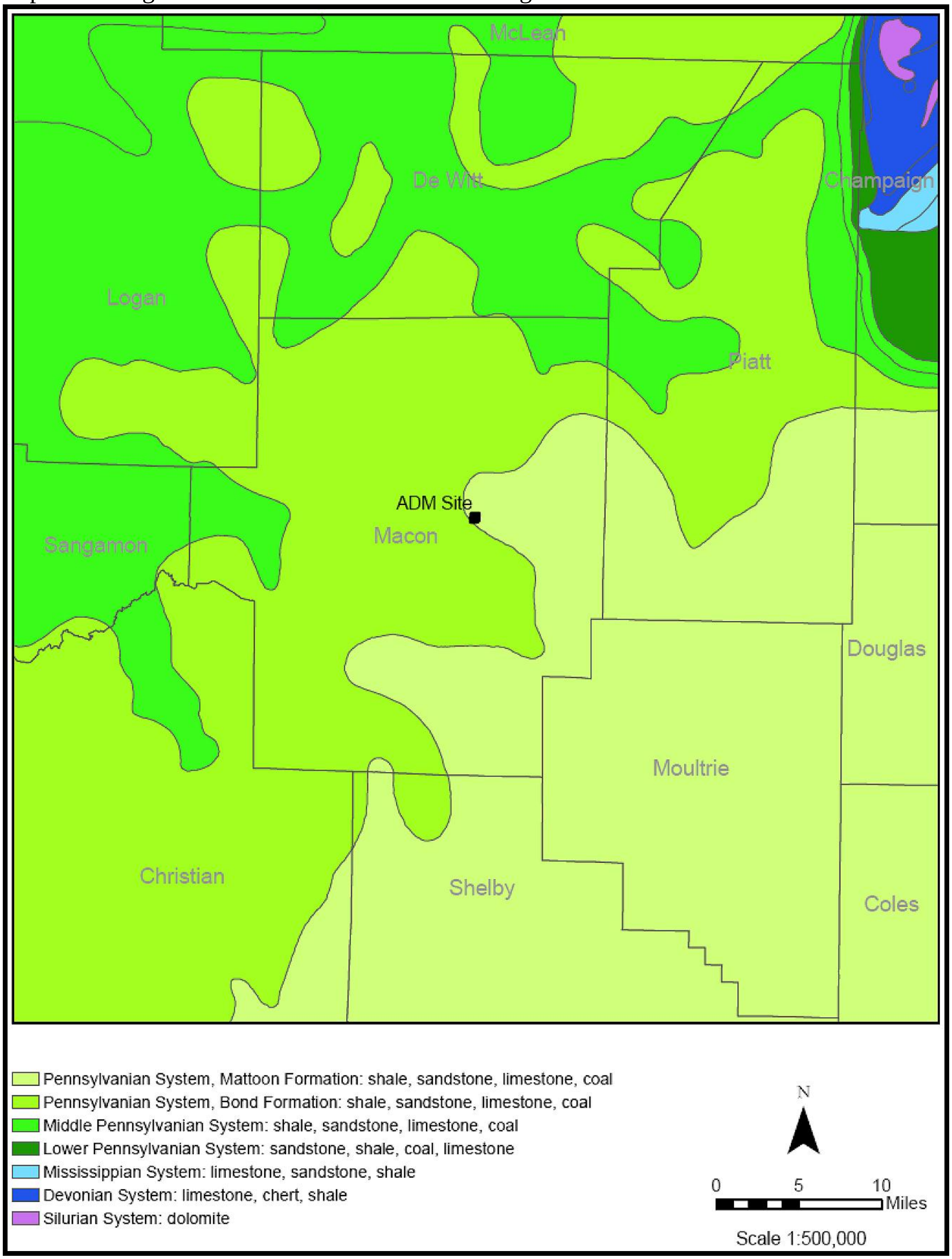


Figure 2-32: Map showing location of cross-section E-E' (modified from Vaiden, 1991).

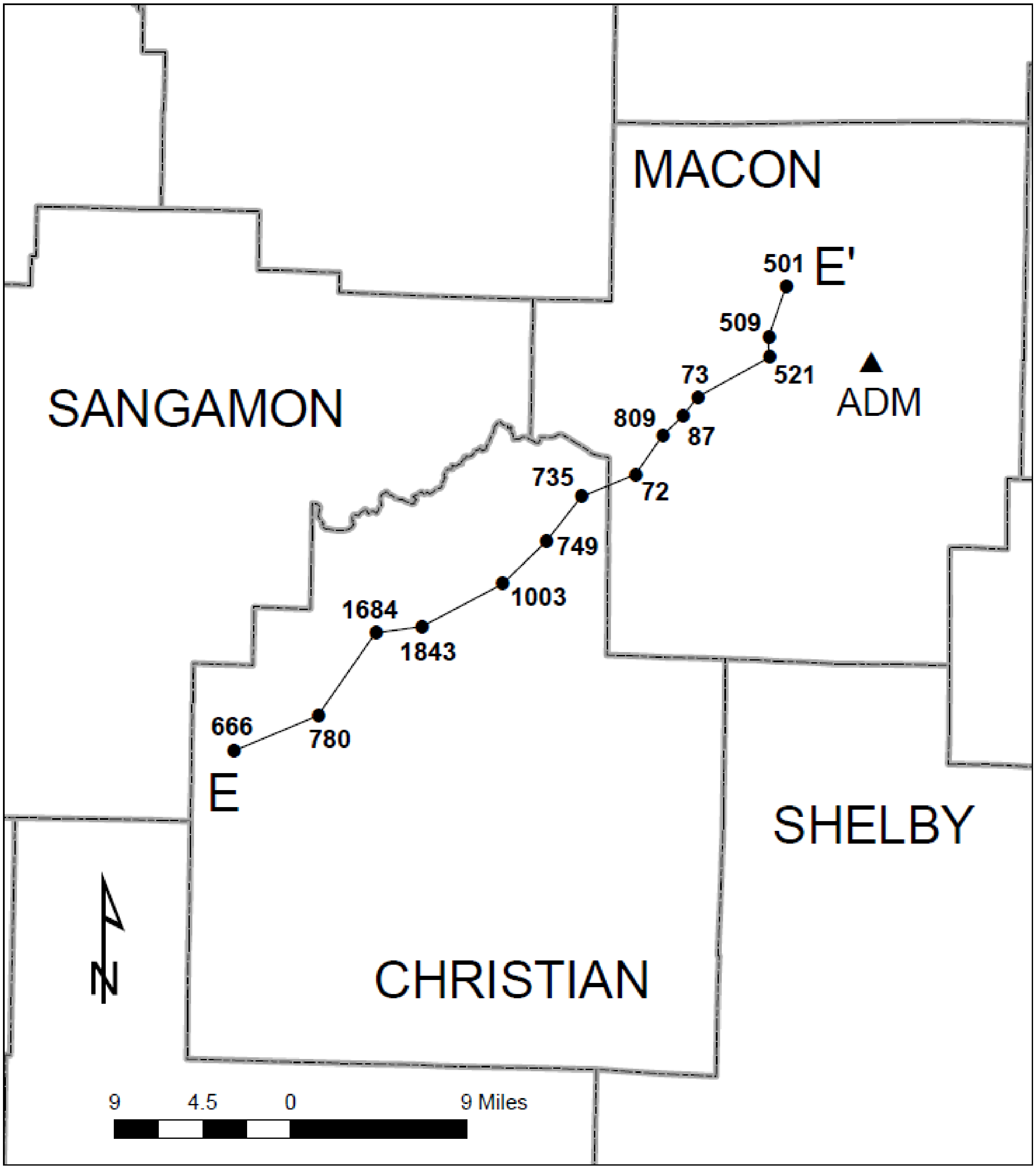


Figure 2-33: Pennsylvanian bedrock cross-section E-E' showing water quality data used to approximate the regional depth to USDW (Vaiden, 1991). Note that the location for well #780 (Section 3, T. 12 N., R. 4 W.) is incorrect. The correct location is Section 3, T. 13 N., R. 3 W.

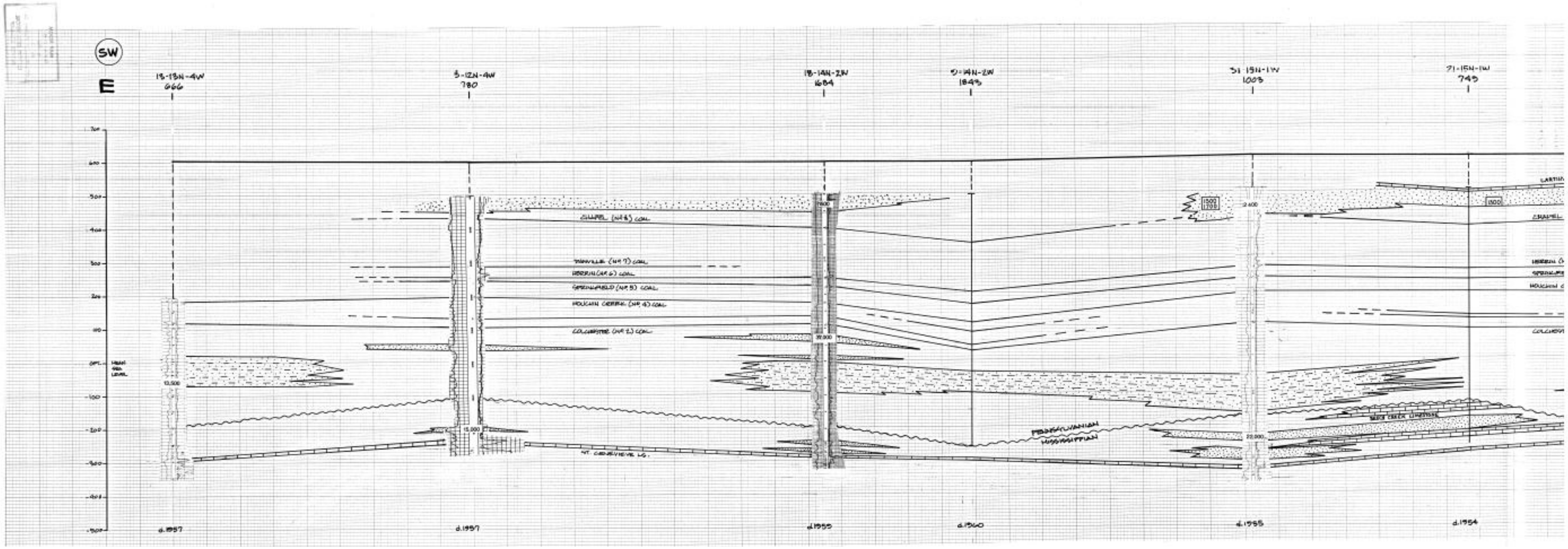


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Figure 2-33 continued from preceding page

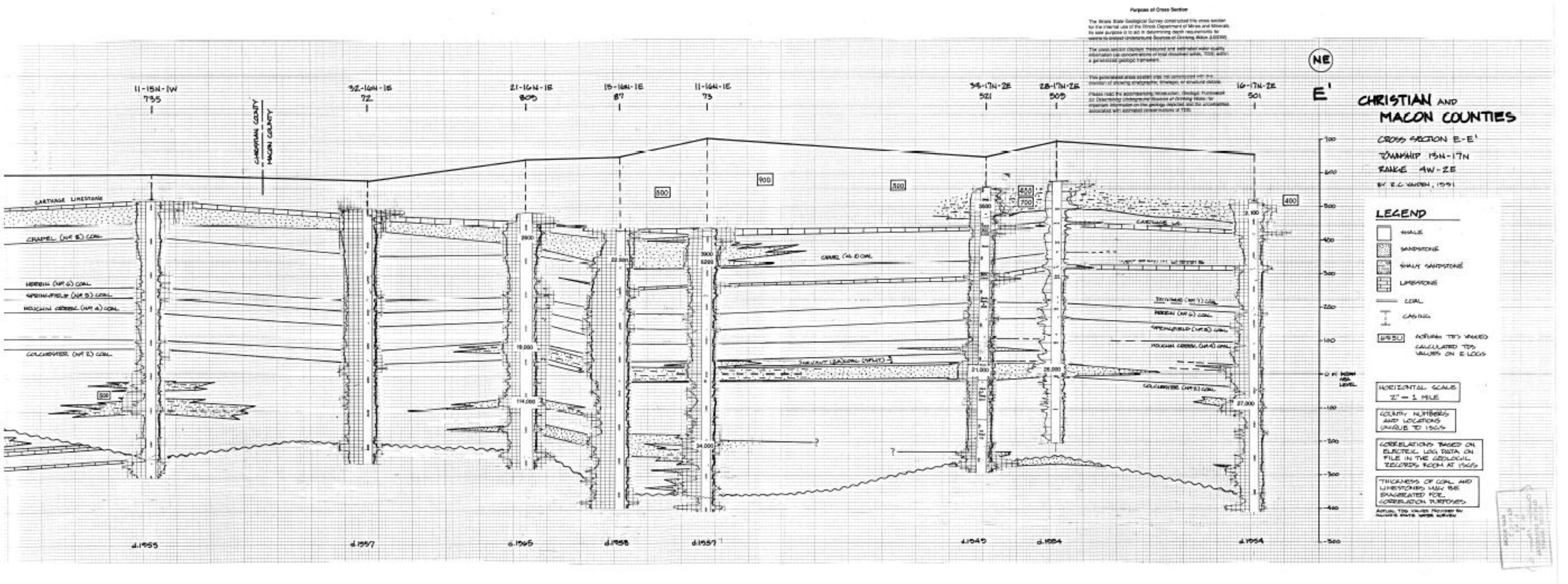
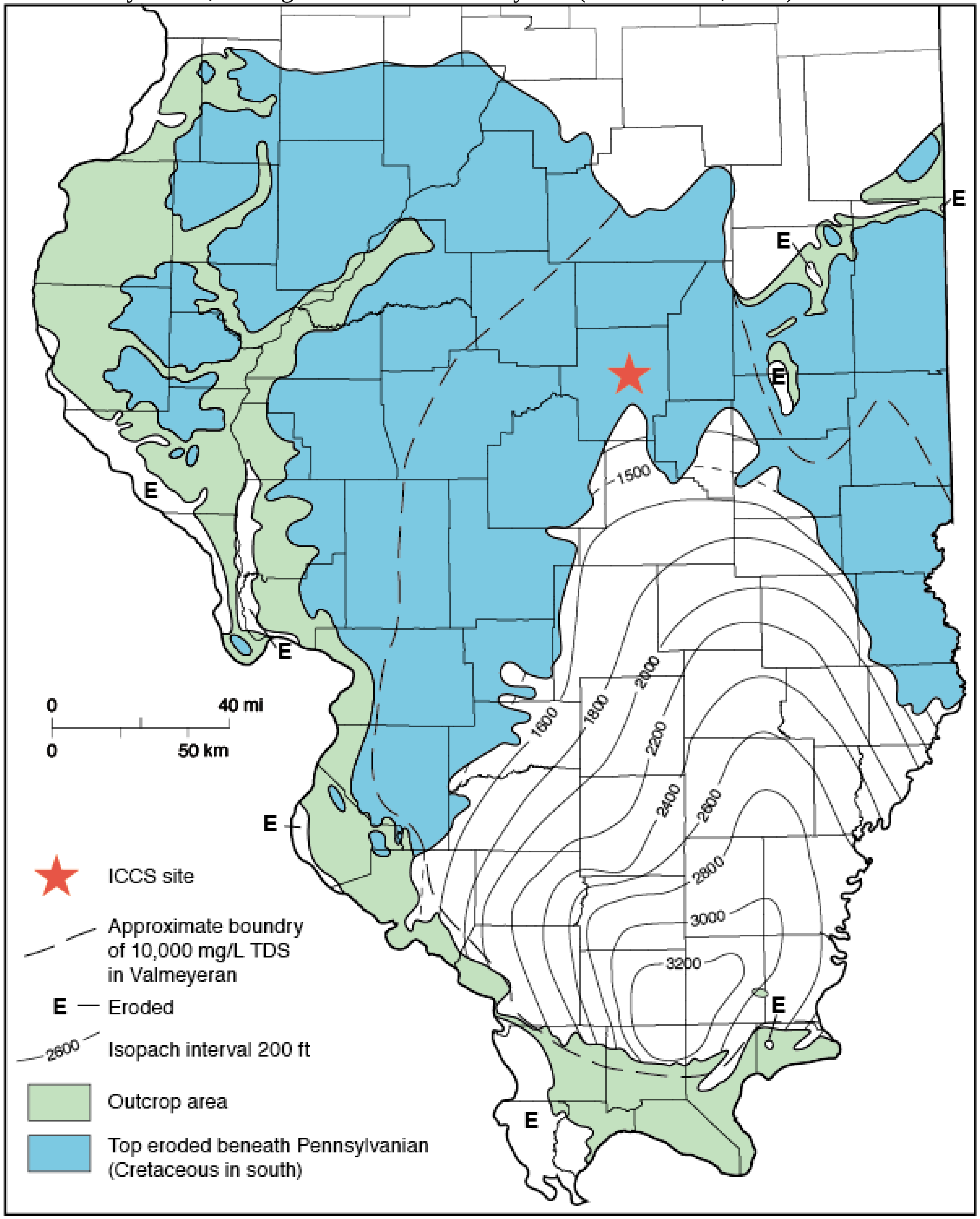
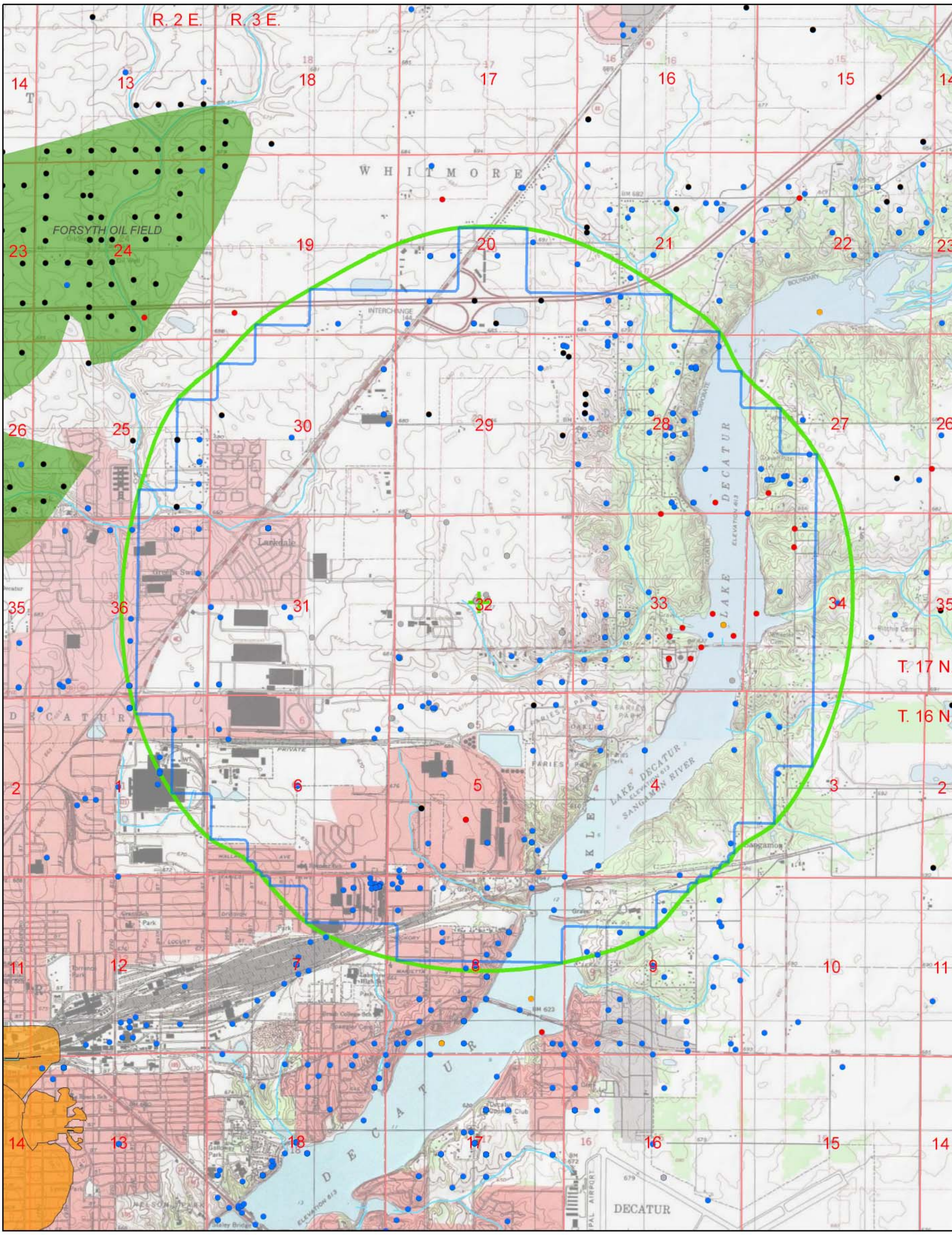


Figure 2-34: Thickness and distribution of the Mississippian System (Willman et al., 1975), and the boundary for 10,000 mg/L TDS in the Valmeyeran (Brower et al., 1989).





Water Well
Oil Well
Stratigraphic Test
Engineering Boring
Other / Unknown
Underground Coal Mine
Generalized Oil Field Area

Area of Review
MESPOP Predicted by Computer Simulations
Center of Area of Review

Base: United States Geological Survey (USGS) 7.5-Minute Topographic Quadrangle map imagery and intermediate-scale DLG streams data, rescaled to 1:36,000. Topographic contour intverval is 5 feet. Tiled topographic map imagery is sourced from scanned paper maps, and is provided by Esri's USGS Topographic Map Service (available at: http://goto.arcgisonline.com/maps/USA_Topo_Maps).

N

0 0.5 1 Miles

Original Printed Scale 1:36,000

Wells, borings, and other penetrations near the proposed IL-ICCS injection well at the ADM Site, Decatur, IL. Well data were obtained from ISGS and ISWS well databases as of May 10, 2011. The green circular feature shows the Area of Review. Updated January 19, 2012 to include drilled or planned ISGS/ICCS project wells.